

観測的“近傍”宇宙論

東京大学 カブリIPMU
林 航平

第4回観測的宇宙論ワークショップ@京大基研

自己紹介

林 航平 (満28歳)

今年3月 PhD. 取得 (東北大学、千葉 柁司教授)

現JSPSポスドク (カブリIPMU、高田昌広教授)

研究分野: 銀河考古学(理論・観測)

- 銀河系・矮小銀河のダークハロー構造
- 銀河系・矮小銀河の化学動力学進化
- HSC・PFSを用いた銀河考古学研究

このトークの目的

- 銀河・矮小銀河スケールにおける Λ CDM理論の諸問題について観測・理論の現状をお伝えする。
- それを踏まえた上で、将来の観測装置及び計画に期待する事をお話する。

アジェンダ

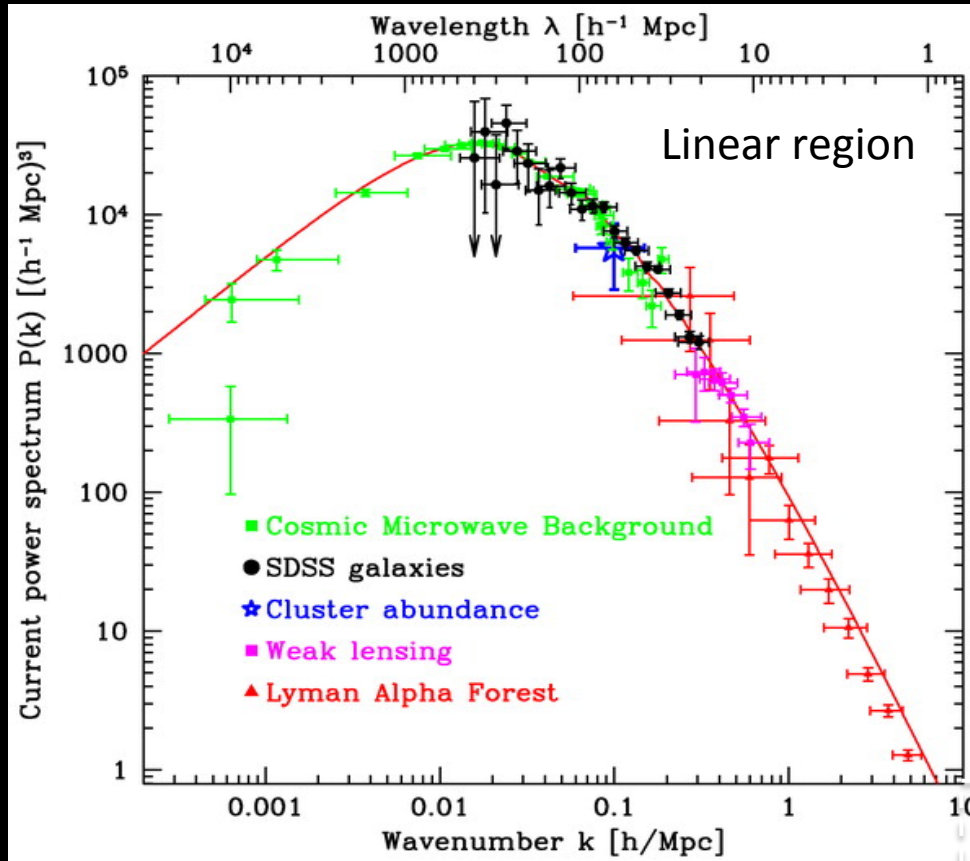
⌘ 観測的近傍宇宙論とは？

⌘ Small Scale Problemsに対する観測・理論の現状

⌘ 観測的近傍宇宙論のこれから

Λ CDM Universe

Tegmark+ 2004



- Large scales ($> 1 \text{ Mpc}$)
-> Remarkable success!
- Small scales ($< 1 \text{ Mpc}$)
-> What's going on?



Non-Linear region

The structures on small scales (< 1 Mpc): Milky Way



恒星系ハローの分布 (Bullock & Johnston 2005)

- Dwarf spheroidal (dSph) galaxy

観測的近傍宇宙論とは

恒星分離に基づく銀河系やその周辺銀河の化学動力的性質から
非線形領域での Λ CDM理論及び銀河形成論について検証を行うこと

Fornax

Sculptor

Faint, no gas, no current SF & diffuse system

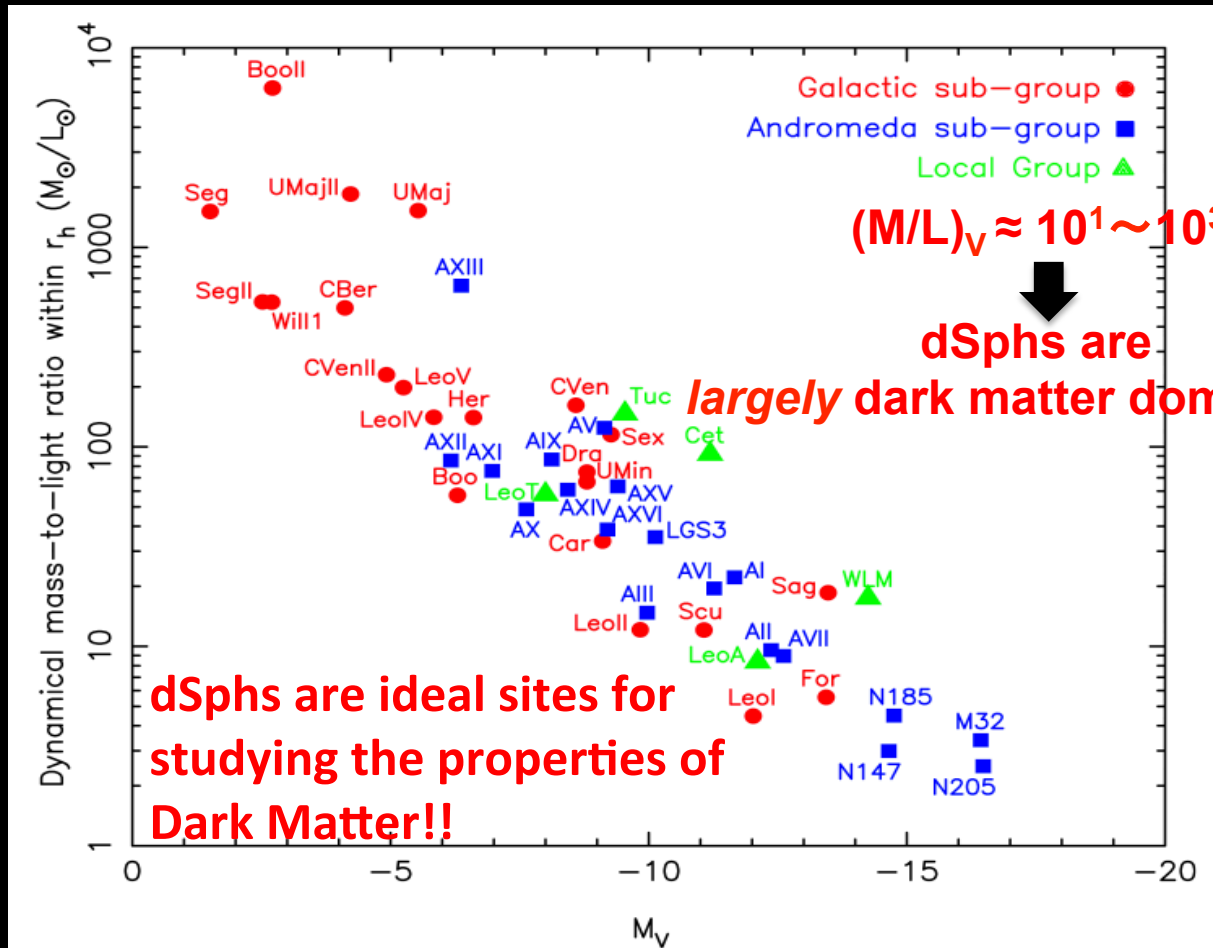
- Stellar streams

恒星分離に基づいた研究が可能！
e.g., 等級、色、空間分布、金属量、
視線速度、固有運動、距離、、

Belokurov+ 2008

Dwarf spheroidal galaxy as a probe of DM

Mass to Light ratio (M/L) within stellar extent in dSphs



McConnachie 2012

Current small scale problems in Λ CDM

❖ Core-cusp problem

- Too steep dark matter density profiles of Λ CDM subhalos.

❖ Missing satellites problem

- Overabundance of Λ CDM subhalos.

❖ Too-big-to-fail problem

- Too concentrated most massive Λ CDM subhalos.

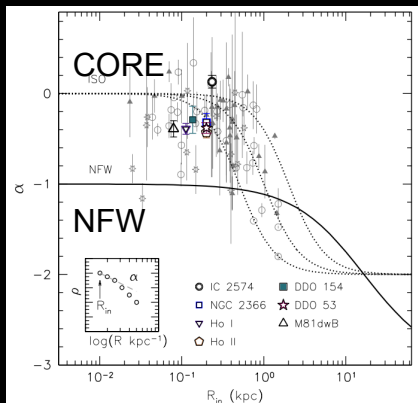
❖ Satellite plane problem

- Anisotropic distribution & coherent motion of dwarf satellites

Solutions:

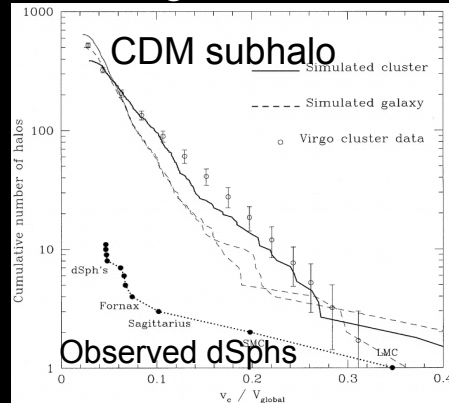
- Baryonic feedbacks?
- Alternative DM models?
- Incomplete observational data?

Core-cusp



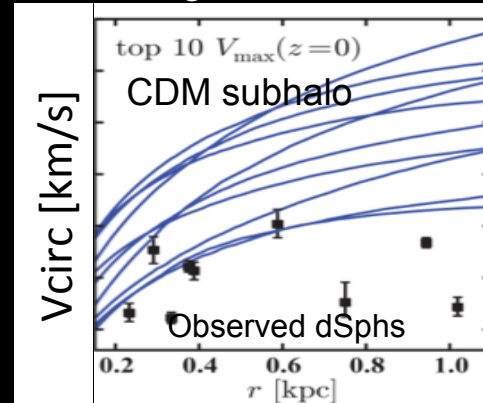
(Oh+ 2011)

Missing satellites



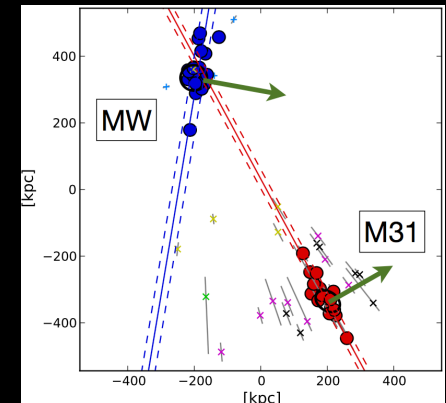
(Moore+ 1999)

Too-big-to-fail



(Boylan-Kolchin+ 2012)

Satellite plane



(Pawlowski+ 2013)

~Is there a core-cusp problem?~

CORE-CUSP PROBLEM

Deriving DM profile from Jeans analysis

$$\sigma_p^2(R) = \frac{2}{I(R)} \int_R^\infty \left(1 - \beta \frac{R^2}{r^2}\right) \frac{\nu(r) v_r^2 r}{\sqrt{r^2 - R^2}} dr$$

$$\beta = 1 - \frac{\sigma_\phi^2 + \sigma_\theta^2}{2\sigma_r^2}$$

observed

not observed

DM halo profile:

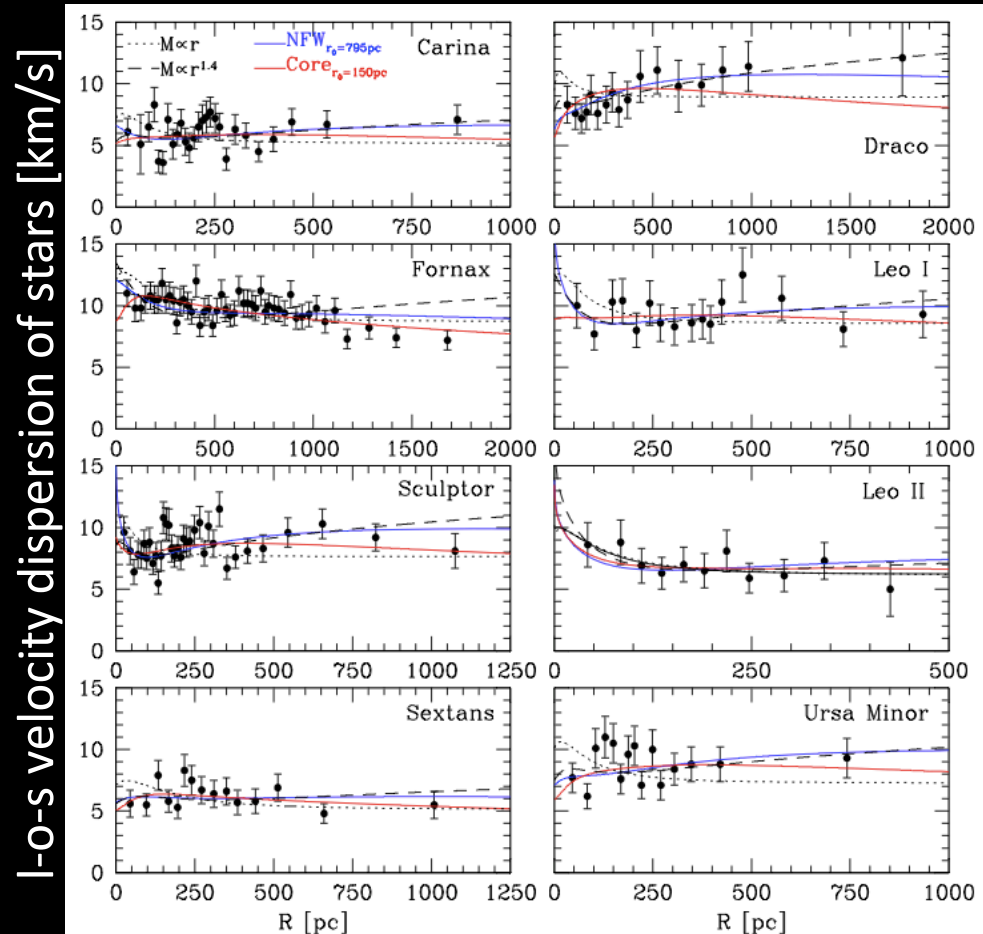
$$\rho(r) = \rho_0 \left(\frac{r}{r_0}\right)^{-\gamma} \left[1 + \left(\frac{r}{r_0}\right)^\alpha\right]^{\frac{\gamma-3}{\alpha}}$$

Stellar profile:

$$I(R) = \frac{L}{\pi R_{\text{half}}^2} \frac{1}{(1 + R^2/R_{\text{half}}^2)^2}$$



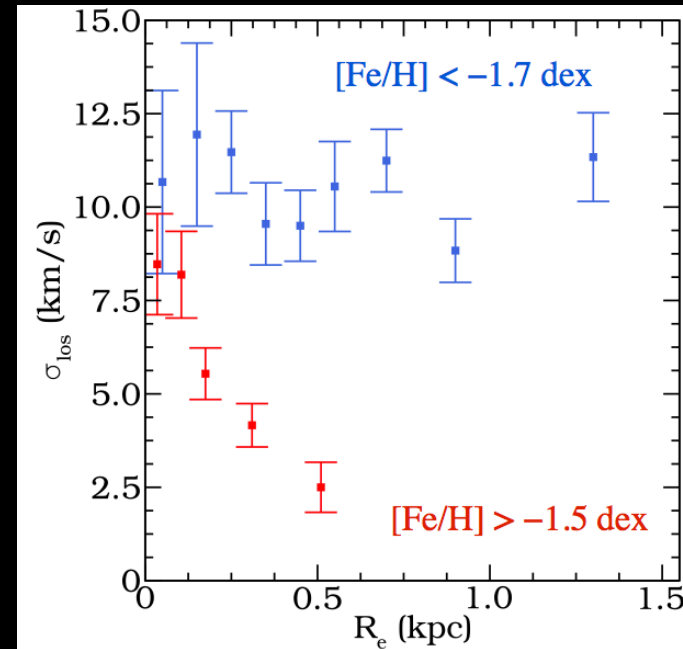
Walker+ 2009



No strong constraints on central profile

Multiple populations in dSphs

Battaglia+ 2008



より詳細な分光観測がされている矮小銀河には

◇metal-richで力学的に冷たい星種族

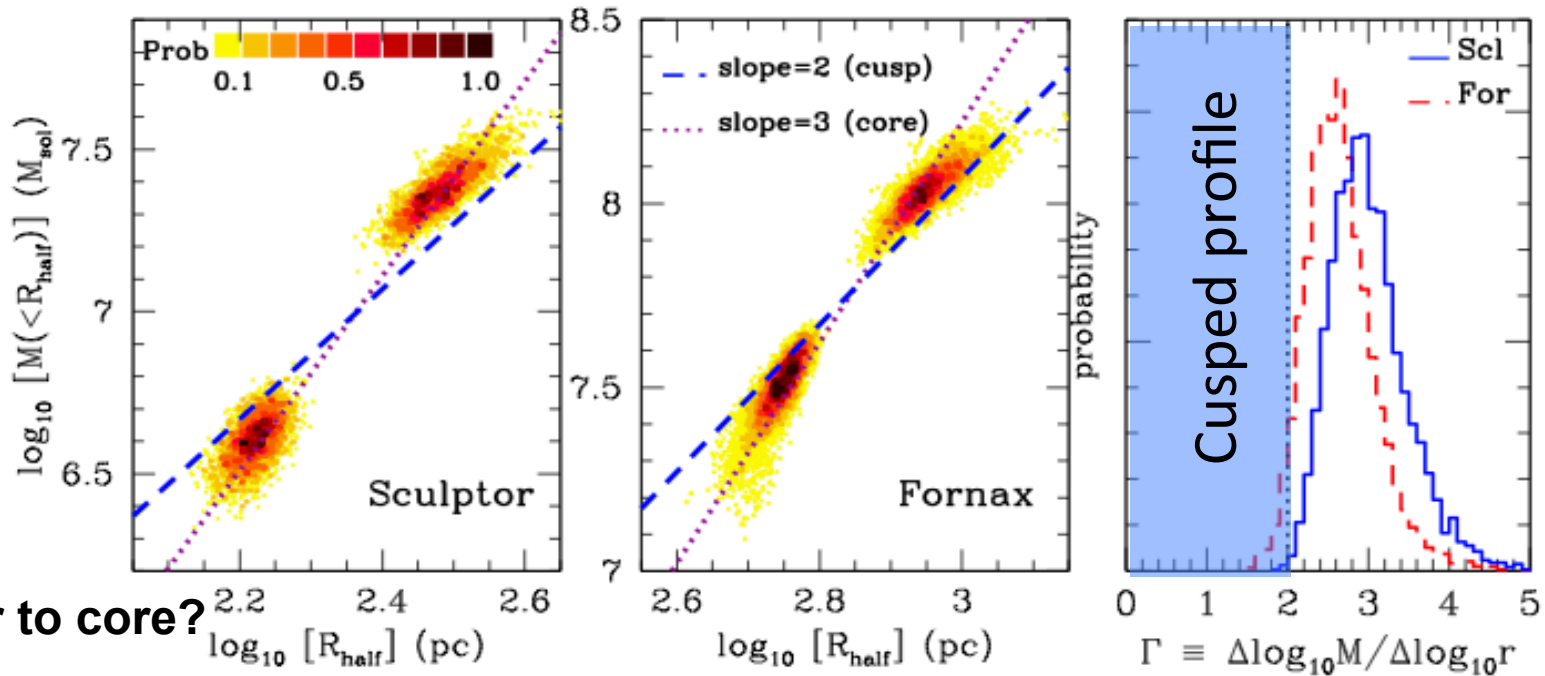
◇metal-poorで力学的に熱い星種族

が存在している。

これらは同じダークマターポテンシャル中を運動していると考えられる。

Logarithmic slope of the mass profile

Walker & Penarrubia + 2011



Prefer to core?

FIG. 10.— *Left, center:* Constraints on halflight radii and masses enclosed therein, for two independent stellar subcomponents in the Fornax and Sculptor dSphs. Plotted points come directly from our final MCMC chains, and color indicates relative likelihood (normalized by the maximum-likelihood value). Overplotted are straight lines indicating the central (and therefore maximum) slopes of cored ($\lim_{r \rightarrow 0} d \log M / d \log r = 3$) and cusped ($\lim_{r \rightarrow 0} d \log M / d \log r = 2$) dark matter halos. *Right:* Posterior PDFs for the slope Γ obtained for Fornax and Sculptor. The vertical dotted line marks the maximum (i.e., central) value of an NFW profile (i.e., cusp with $\gamma_{\text{DM}} = 1$, $\lim_{r \rightarrow 0} [d \log M / d \log r] = 2$). These measurements rule out NFW and/or steeper cusps ($\gamma_{\text{DM}} \geq 1$) with significance $s \gtrsim 96\%$ (Fornax) and $s \gtrsim 99\%$ (Sculptor).

$$\Gamma \equiv \frac{\Delta \log M}{\Delta \log r} = \frac{\log[M(r_{h,2})/M(r_{h,1})]}{\log[r_{h,2}/r_{h,1}]} \approx 1 + \frac{\log[\sigma_{V,2}^2/\sigma_{V,1}^2]}{\log[r_{h,2}/r_{h,1}]}$$

$$\Gamma \lesssim 3$$

: cored profile

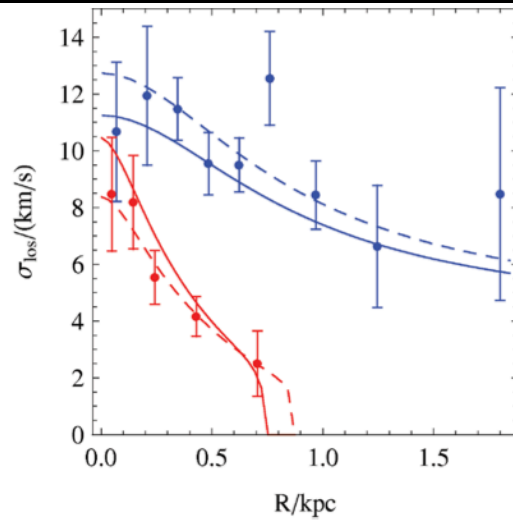
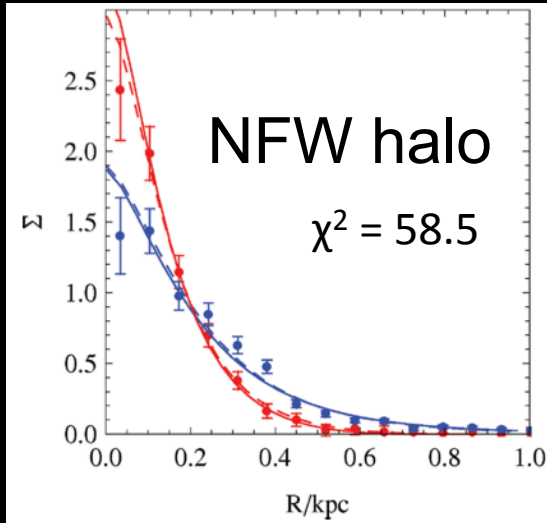
$$\Gamma \lesssim 3 - \gamma$$

$$(\gamma \geq 1)$$

: cusped profile

Deriving DM profile from other methods

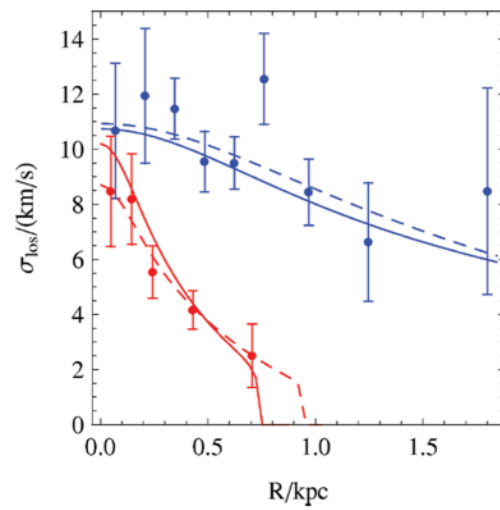
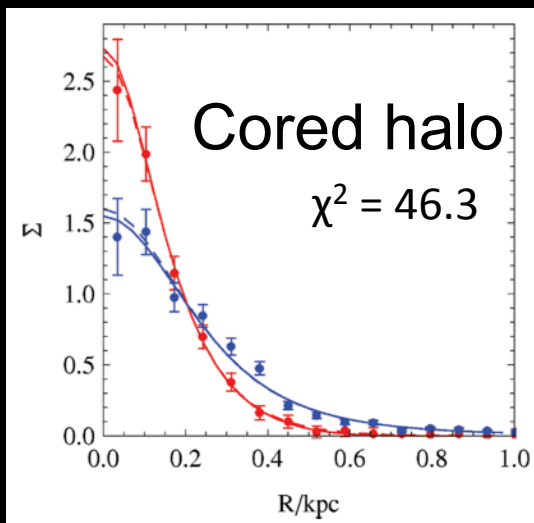
• Distribution Function (Amorisco & Evans 2012)



$$f_{\text{MK}}(E, L) = \frac{\rho_{*,0}}{(2\pi\sigma^2)^{3/2}} \exp\left(\frac{-L^2}{2r_a^2\sigma^2}\right) f_{\text{K}}(E),$$

where

$$f_{\text{K}}(E) = \exp\left[\frac{\Phi(r_t) - E}{\sigma^2}\right] - 1.$$



Core modelの方がfittingは良い。
(NFWハローでもまあまあ再現出来ているが、中心集中度がN体計算から得られているものより、明らかに小さい。)

Deriving DM profile from other methods

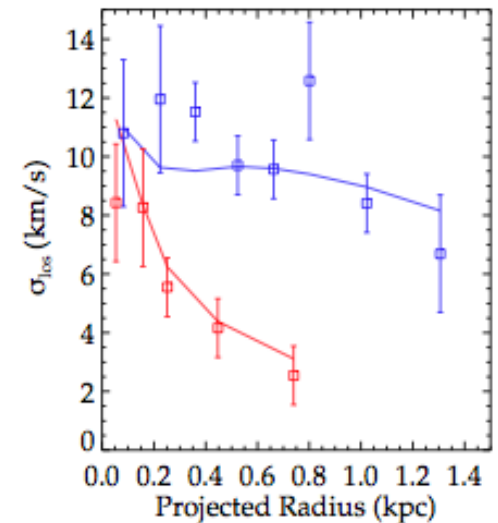
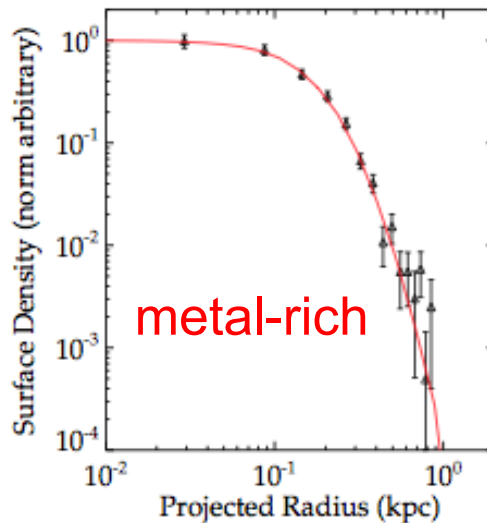
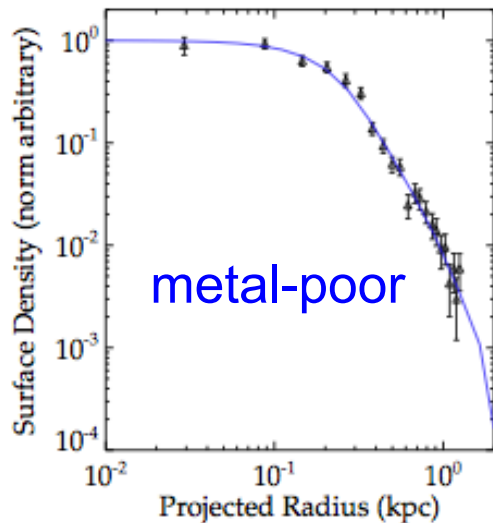
- Distribution Function (Strigari+ 2014)

$$f(E, J) = g(J)h(E)$$

$$g(J) = \begin{cases} [1 + (J/J_\beta)^{-b}]^{-1}, & \text{for } b \leq 0 \\ 1 + (J/J_\beta)^b, & \text{for } b > 0. \end{cases}$$

$$h(E) = \begin{cases} NE^\alpha (E^q + E_c^q)^{d/q} (\Phi_{lim} - E)^e & \text{for } E < \Phi_{lim} \\ 0 & \text{for } E \geq \Phi_{lim} \end{cases}$$

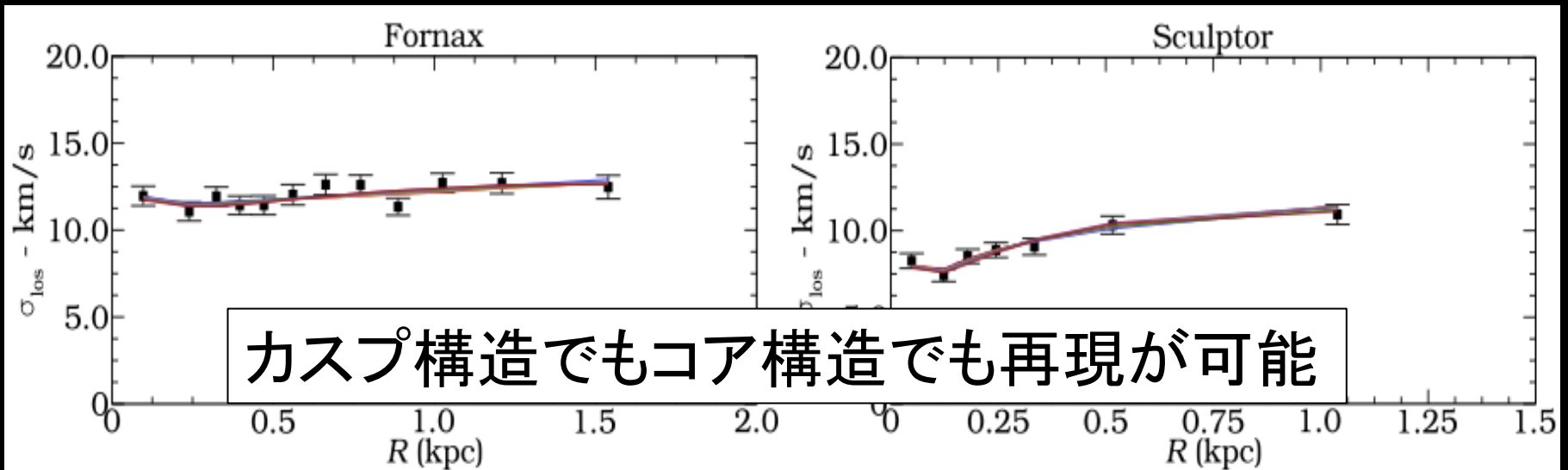
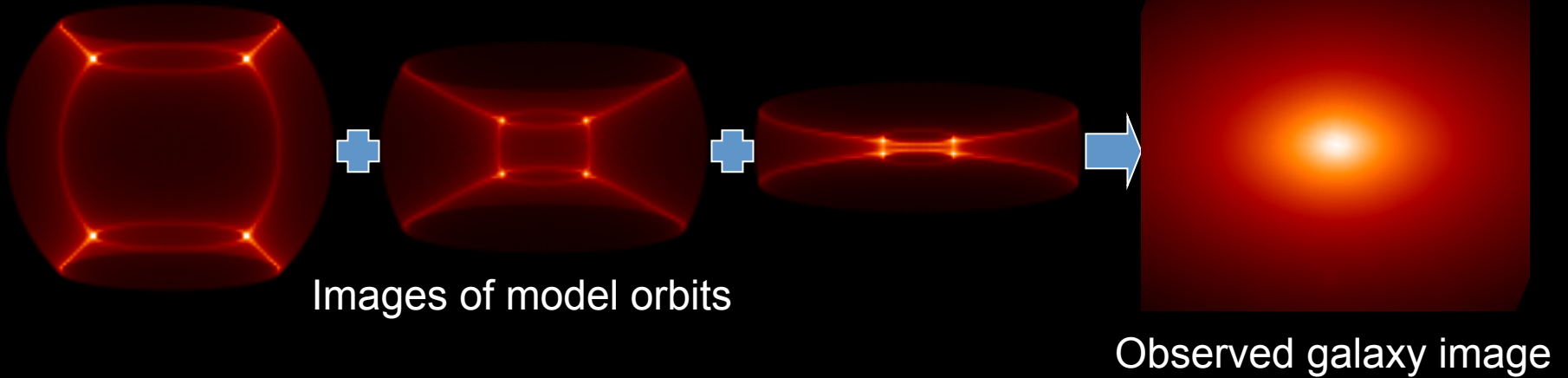
分布関数を以下の形にして、Amorisco & Evans (2012)同様、Sculptorの2種族星成分を NFWハロー で再現した。



Deriving DM profile from other methods

- Schwarzschild method (Breddels+ 2012, Breddels & Helmi 2013)

Schwarzschild 1979; Vandervoort 1984



Core or Cusp?

CORE

A METHOD FOR MEASURING (SLOPES OF) THE MASS PROFILES OF DWARF SPHEROIDAL GALAXIES

MATTHEW G. WALKER^{1,2,3} & JORGE PEÑARRUBIA²

Dark matter cores and cusps: the case of multiple stellar populations in dwarf spheroidals

N. C. Amorisco* and N. W. Evans*

THE KINEMATIC STATUS AND MASS CONTENT OF THE SCULPTOR DWARF SPHEROIDAL GALAXY¹

G. BATTAGLIA,^{2,3} A. HELMI,³ E. TOLSTOY,³ M. IRWIN,⁴ V. HILL,⁵ AND P. JABLONKA⁶

THE DARK MATTER DENSITY PROFILE OF THE FORNAX DWARF

JOHN R. JARDEL AND KARL GEBHARDT

The core size of the Fornax dwarf spheroidal

N. C. Amorisco,^{1,2} A. Agnello¹ and N. W. Evans^{1*}

A VIRIAL CORE IN THE SCULPTOR DWARF SPHEROIDAL GALAXY

A. AGNELLO AND N. W. EVANS

CUSP

Dynamical models for the Sculptor dwarf spheroidal in a Λ CDM universe

Louis E. Strigari¹, Carlos S. Frenk² and Simon D. M. White³

Kinematics of Milky Way satellites in a Lambda cold dark matter universe

Louis E. Strigari,^{1*} Carlos S. Frenk² and Simon D. M. White³

MEASURING DARK MATTER PROFILES NON-PARAMETRICALLY IN DWARF SPHEROIDALS: AN APPLICATION TO DRACO

JOHN R. JARDEL¹, KARL GEBHARDT¹, MAXIMILIAN FABRICIUS², NIV DRORY³, AND MICHAEL J. WILLIAMS²

VARIATIONS IN A UNIVERSAL DARK MATTER PROFILE FOR DWARF SPHEROIDALS

JOHN R. JARDEL AND KARL GEBHARDT

On the Dark Matter profile in Sculptor: Breaking the β degeneracy with Virial Shape Parameters

Thomas Richardson^{1*}, Malcolm Fairbairn¹

より数多の観測精度の良い分光データが必要

CANNOT decide yet

COMPLEXITY ON DWARF GALAXIES SCALE: A BIMODAL DISTRIBUTION FUNCTION IN SCULPTOR

MAARTEN A. BREDDELS AND AMINA HELMI

Orbit-based dynamical models of the Sculptor dSph galaxy

Maarten A. Breddels,^{1*} A. Helmi,¹ R. C. E. van den Bosch,² G. van de Ven² and G. Battaglia³

Model comparison of the dark matter profiles of Fornax, Sculptor, Carina and Sextans

Maarten A. Breddels and Amina Helmi

A UNIVERSAL MASS PROFILE FOR DWARF SPHEROIDAL GALAXIES?*

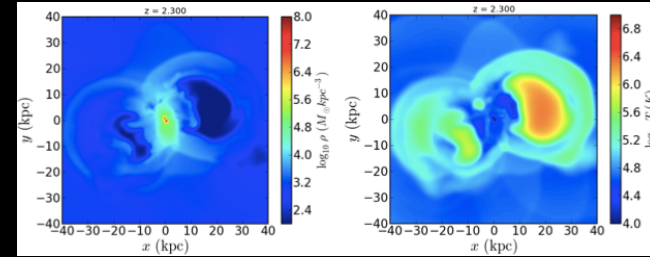
MATTHEW G. WALKER¹, MARIO MATEO², EDWARD W. OLSZEWSKI³, JORGE PEÑARRUBIA¹, N. WYN EVANS¹, AND GERARD GILMORE¹

Cores in Classical Dwarf Spheroidal Galaxies? A Dispersion-Kurtosis Jeans Analysis Without Restricted Anisotropy

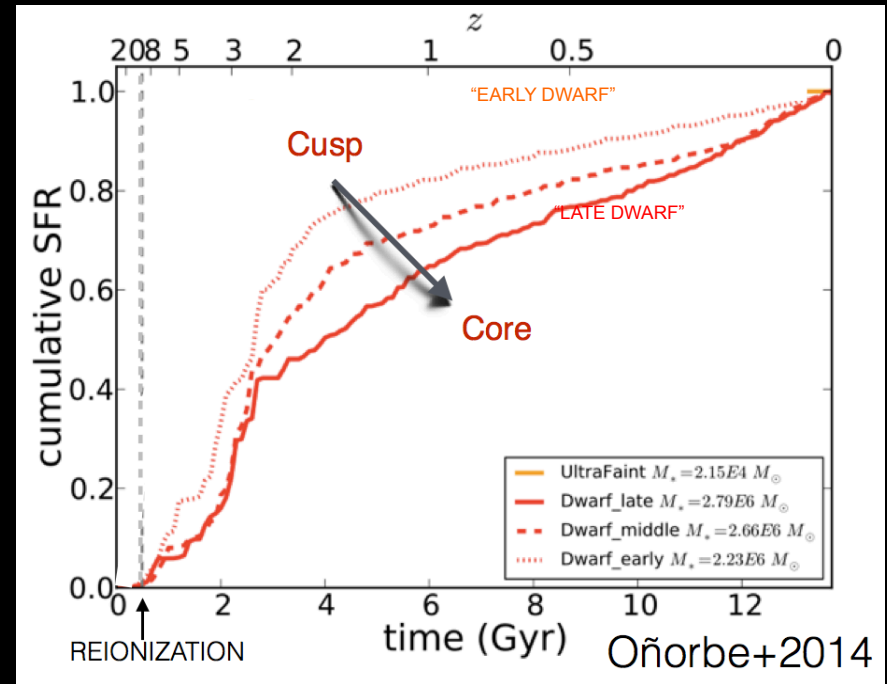
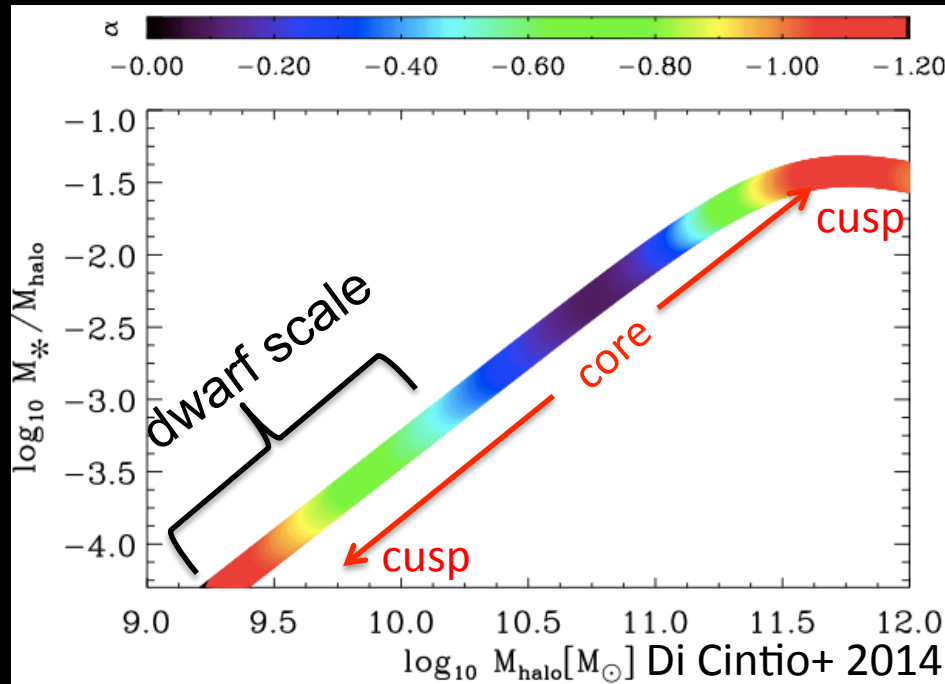
Thomas Richardson^{1*}, Malcolm Fairbairn¹

New insight into inner profile of DM halo

N-body + hydro simulation in Λ CDM Universe

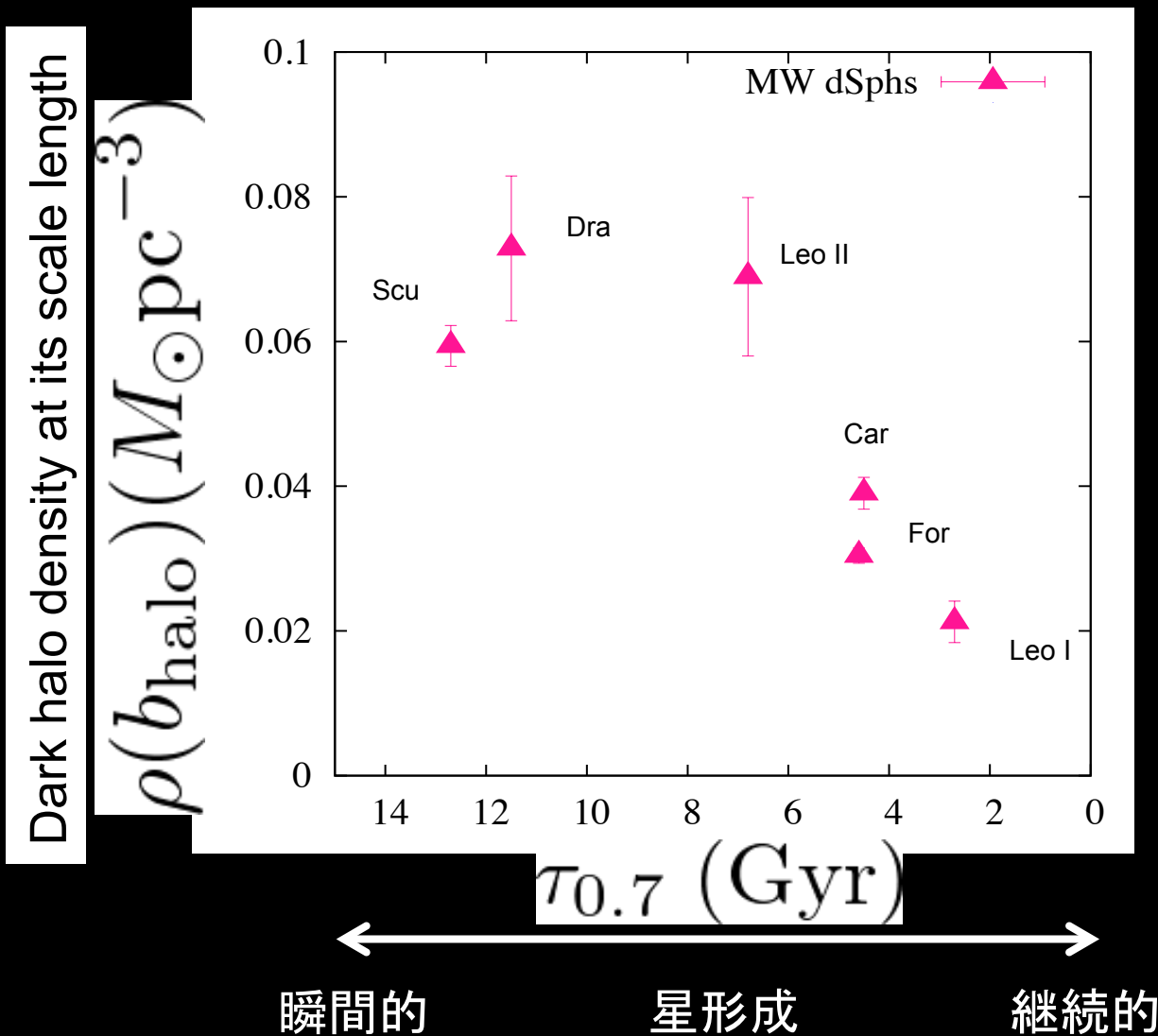


ダークハロー密度分布は星-ダークハロー質量比や星形成史に大きく依存する



Possible relation between DM density and SFH

Hayashi & Chiba 2015b

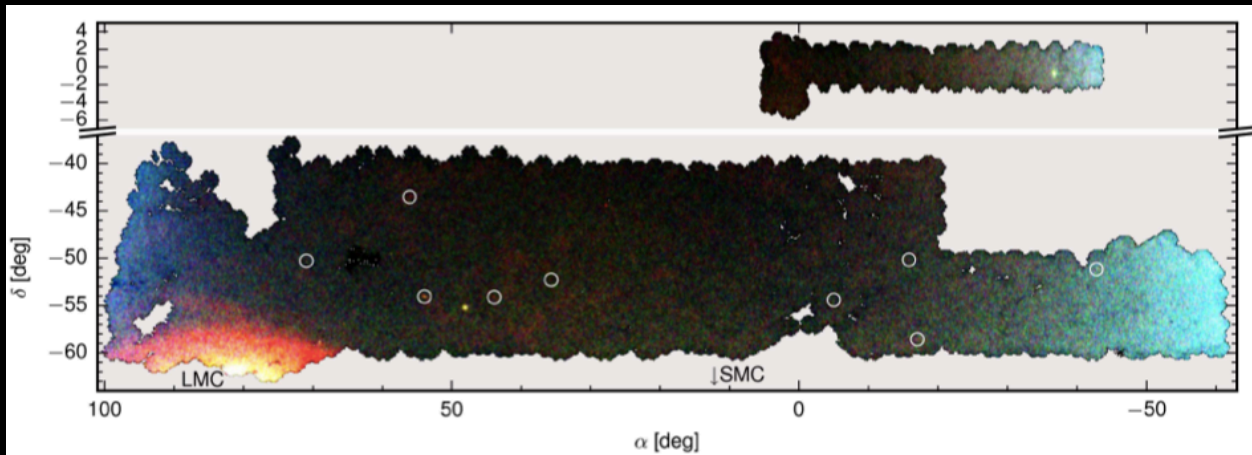


~Discover new hopes~

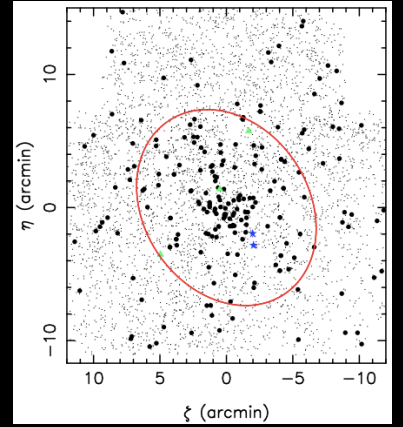
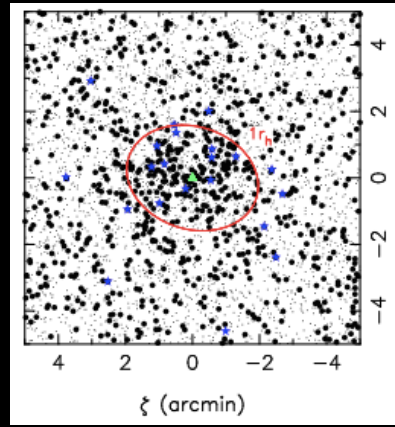
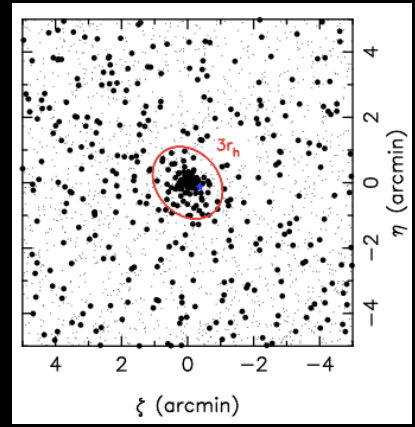
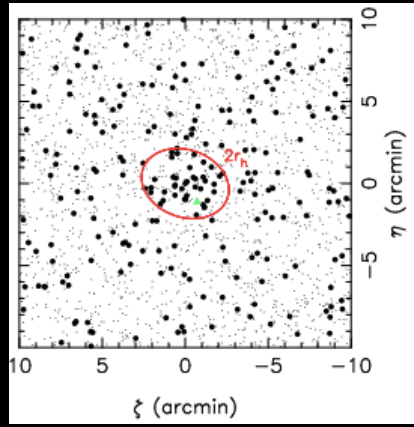
MISSING SATELLITE PROBLEM

Discovering NEW faint dwarfs in MW

• 9 newly faint dwarfs is discovered from Dark Energy Survey (Koposov+ 2015)



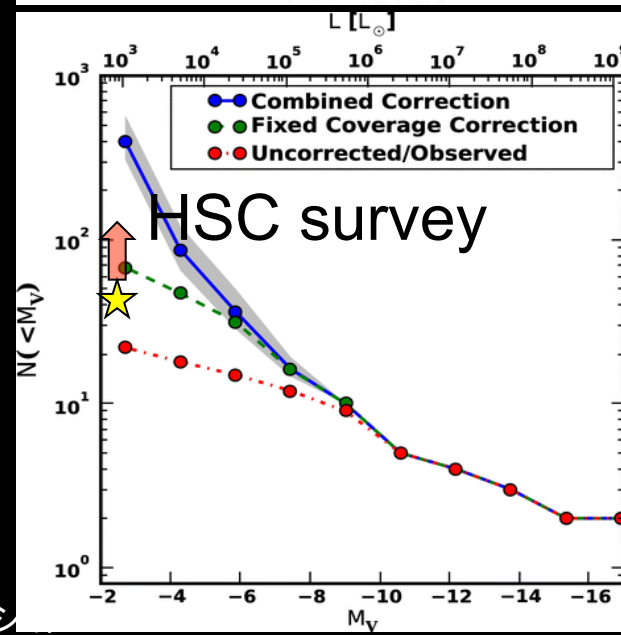
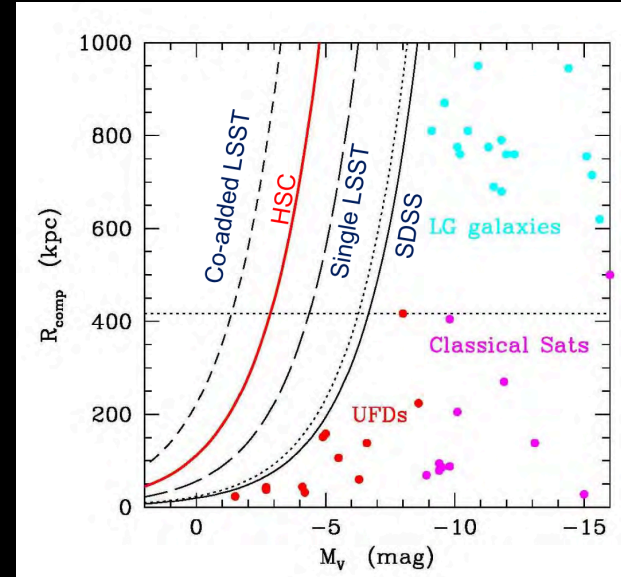
• 4 newly faint dwarfs are discovered from Pan-STARRS 1 3π Survey



Current status and Future prospects

McConnachie (2012): 27 satellites + new 13 UFDs

Table 1 Basic Information					
(1) Galaxy	(2) Other Names	(3)	(4)	(5) R.A. J2000	(6) Decl. J2000
The MW sub-group (in order of distance from the MW)					
The Galaxy	The MW	G	S(B)bc	17 ^h 45 ^m 40 ^s .0	-29 ^d 00 ^m 28 ^s
Canis Major		G	????	07 ^h 12 ^m 35 ^s .0	-27 ^d 40 ^m 00 ^s
Sagittarius dSph		G	dSph	18 ^h 55 ^m 19 ^s .5	-30 ^d 32 ^m 43 ^s
Segue (I)		G	dSph	10 ^h 07 ^m 04 ^s .0	+16 ^d 04 ^m 55 ^s
Ursa Major II		G	dSph	08 ^h 51 ^m 30 ^s .0	+63 ^d 07 ^m 48 ^s
Bootes II		G	dSph	13 ^h 58 ^m 00 ^s .0	+12 ^d 51 ^m 00 ^s
Segue II		G	dSph	02 ^h 19 ^m 16 ^s .0	+20 ^d 10 ^m 31 ^s
Willman 1	SDSS J1049+5103	G	dSph	10 ^h 49 ^m 21 ^s .0	+51 ^d 03 ^m 00 ^s
Coma Berenices		G	dSph	12 ^h 26 ^m 59 ^s .0	+23 ^d 54 ^m 15 ^s
Bootes III		G	dSph?	13 ^h 57 ^m 12 ^s .0	+26 ^d 48 ^m 00 ^s
LMC	Nubecula Major	G	Irr	05 ^h 23 ^m 34 ^s .5	-69 ^d 45 ^m 22 ^s
SMC	Nubecula Minor NGC 292	G	dIrr	00 ^h 52 ^m 44 ^s .8	-72 ^d 49 ^m 43 ^s
Bootes (I)		G	dSph	14 ^h 00 ^m 06 ^s .0	+14 ^d 30 ^m 00 ^s
Draco	UGC 10822 DDO 208	G	dSph	17 ^h 20 ^m 12 ^s .4	+57 ^d 54 ^m 55 ^s
Ursa Minor	UGC 9749 DDO 199	G	dSph	15 ^h 09 ^m 08 ^s .5	+67 ^d 13 ^m 21 ^s
Sculptor		G	dSph	01 ^h 00 ^m 09 ^s .4	-33 ^d 42 ^m 33 ^s
Sextans (I)		G	dSph	10 ^h 13 ^m 03 ^s .0	-01 ^d 36 ^m 53 ^s
Ursa Major (I)		G	dSph	10 ^h 34 ^m 52 ^s .8	+51 ^d 55 ^m 12 ^s
Carina		G	dSph	06 ^h 41 ^m 36 ^s .7	-50 ^d 57 ^m 58 ^s
Hercules		G	dSph	16 ^h 31 ^m 02 ^s .0	+12 ^d 47 ^m 30 ^s
Fornax		G	dSph	02 ^h 39 ^m 59 ^s .3	-34 ^d 26 ^m 57 ^s
Leo IV		G	dSph	11 ^h 32 ^m 57 ^s .0	-00 ^d 32 ^m 00 ^s
Canes Venatici II	SDSS J1257+3419	G	dSph	12 ^h 57 ^m 10 ^s .0	+34 ^d 19 ^m 15 ^s
Leo V		G	dSph	11 ^h 31 ^m 09 ^s .6	+02 ^d 13 ^m 12 ^s
Pisces II		G	dSph	22 ^h 58 ^m 31 ^s .0	+05 ^d 57 ^m 09 ^s
Canes Venatici (I)		G	dSph	13 ^h 28 ^m 03 ^s .5	+33 ^d 33 ^m 21 ^s
Leo II	Leo B UGC 6253 DDO 93	G	dSph	11 ^h 13 ^m 28 ^s .8	+22 ^d 09 ^m 06 ^s
Leo I	UGC 5470 DDO 74 Regulus Dwarf	G/L	dSph	10 ^h 08 ^m 28 ^s .1	+12 ^d 18 ^m 23 ^s



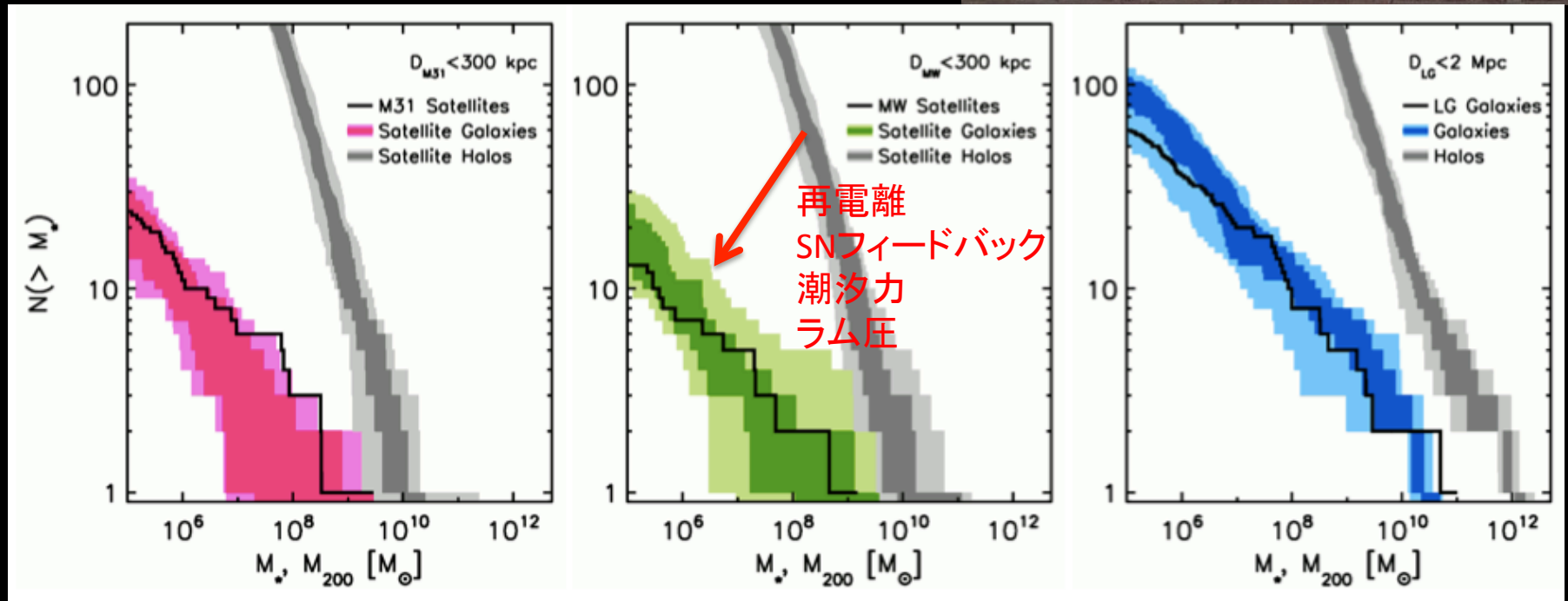
Tollerud+ 2008

Can baryon solve this issue?

The APOSTLE simulations: solutions to the Local Group's cosmic puzzles

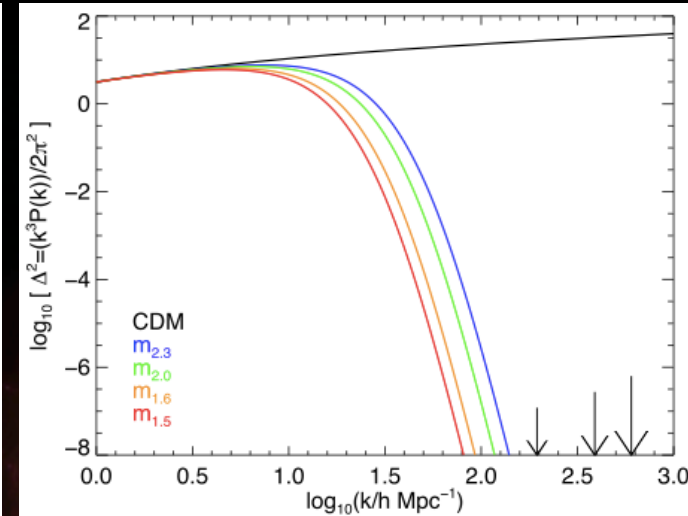
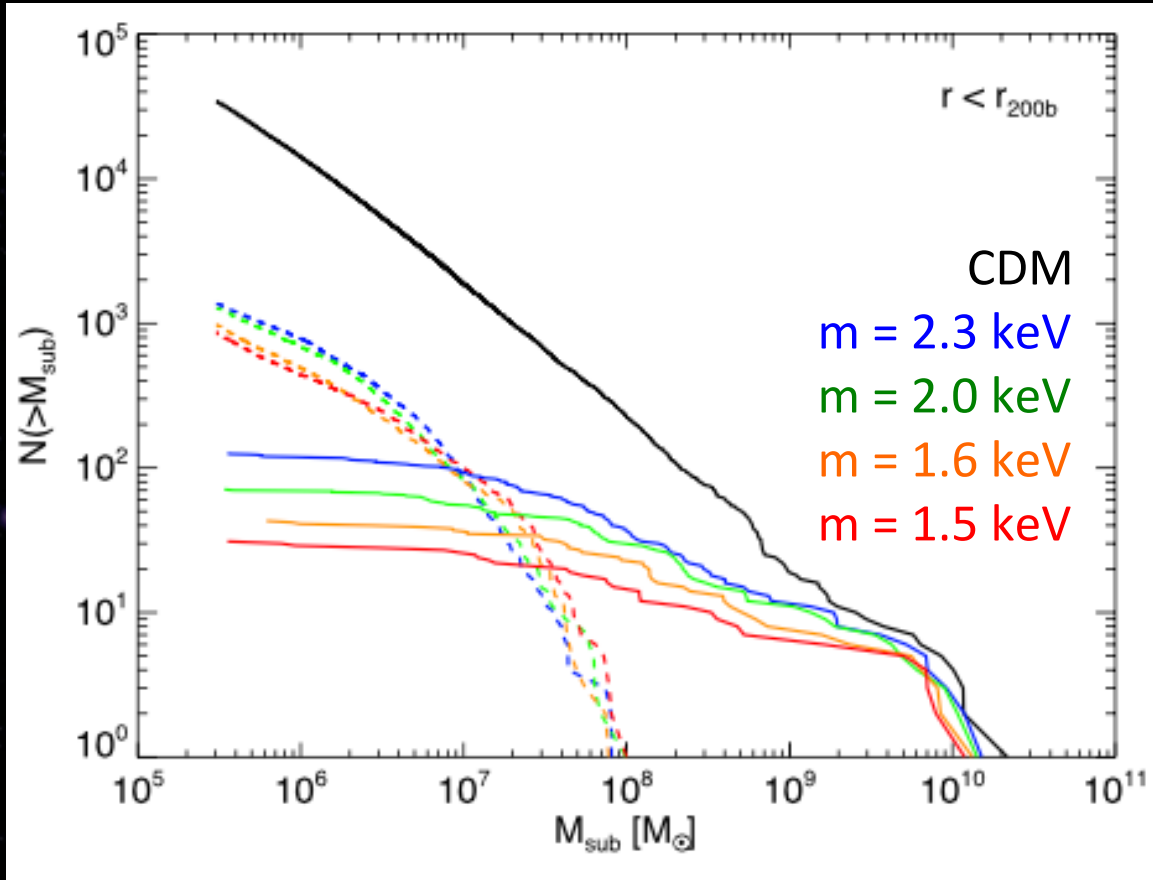
Till Sawala^{1,2*}, Carlos S. Frenk¹, Azadeh Fattahi³, Julio F. Navarro^{3,4}, Richard G. Bower¹, Robert A. Crain⁵, Claudio Dalla Vecchia^{6,7}, Michelle Furlong¹, John. C. Helly¹, Adrian Jenkins¹, Kyle A. Oman², Matthieu Schaller¹, Joop Schaye⁸, Tom Theuns¹, James Trayford¹ and Simon D. M. White⁹

Λ CDM理論の枠組みの中で
バリオンの効果によって、
局所銀河群のMSPは解決可能



Can WDM help it?

Lovell+ 2014



WDM model:
小さな空間スケールの
構造を作りにくくする。

MSPを解決可能

CDM+バリオン効果 vs. Warm dark matter
どっちが正しい？

~Massive Failure?~

TOO-BIG-TO-FAIL PROBLEM

Beyond the Milky Way

Circular velocity:

$$V_{\text{circ}} = \sqrt{\frac{GM(< r)}{r}}$$

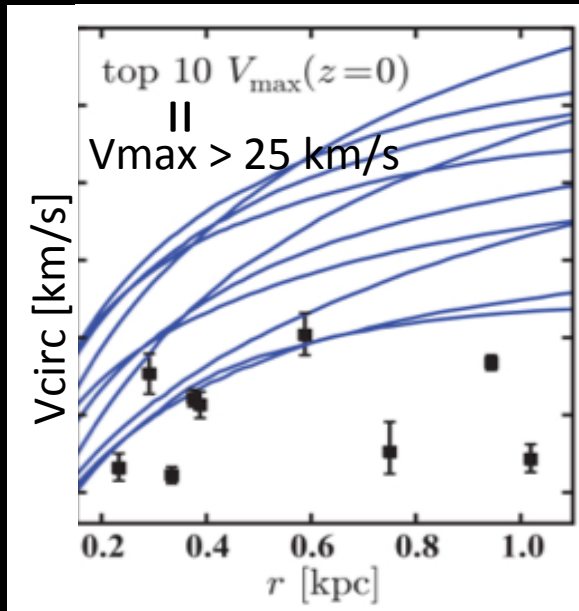
MW

Observed value:

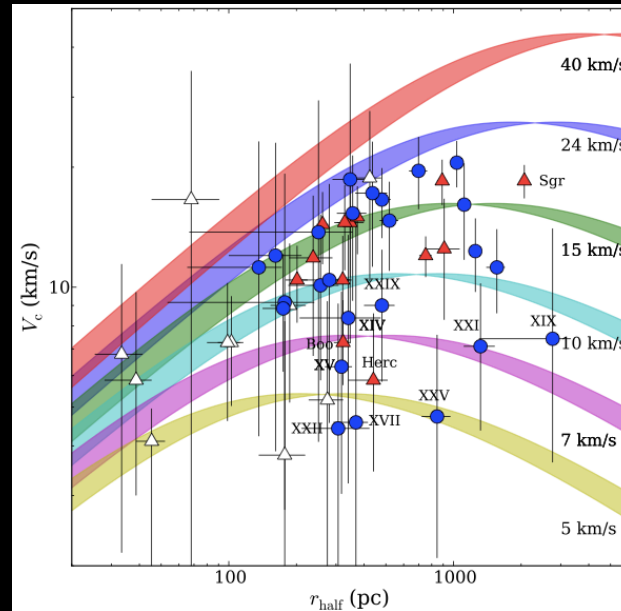
$$V_{\text{circ}}(r_{\text{half}}) = \sqrt{\frac{GM(< r_{\text{half}})}{r_{\text{half}}}}$$

Andromeda

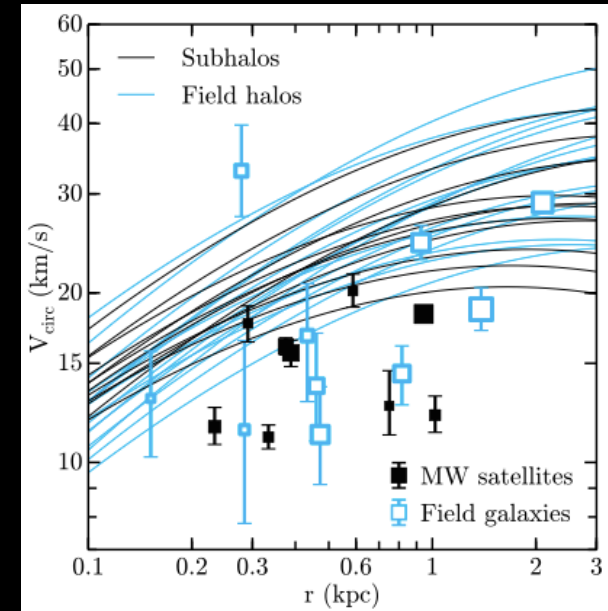
LG galaxies



Boylan-Kolchin+ 2012



Collins+ 2013



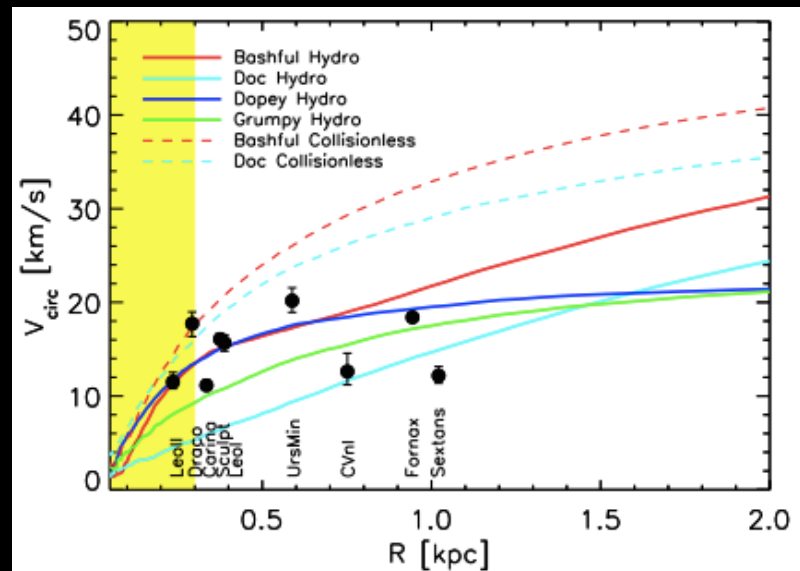
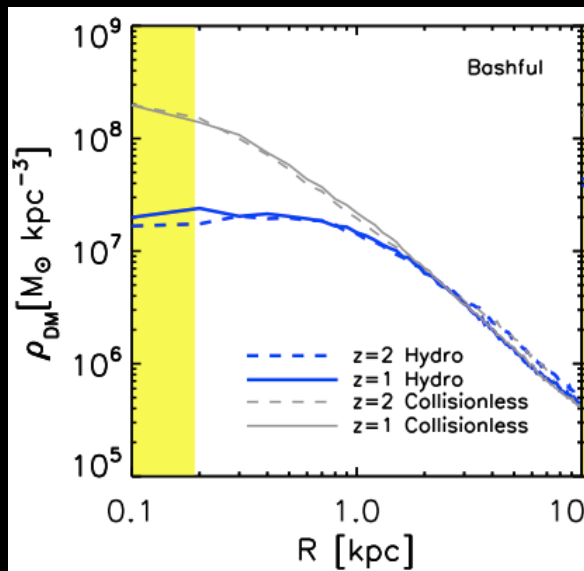
Garrison-Kimmel+ 2014

TBTF問題はMWだけでなく、局所銀河群全体の問題に

To mitigate TBTF problem

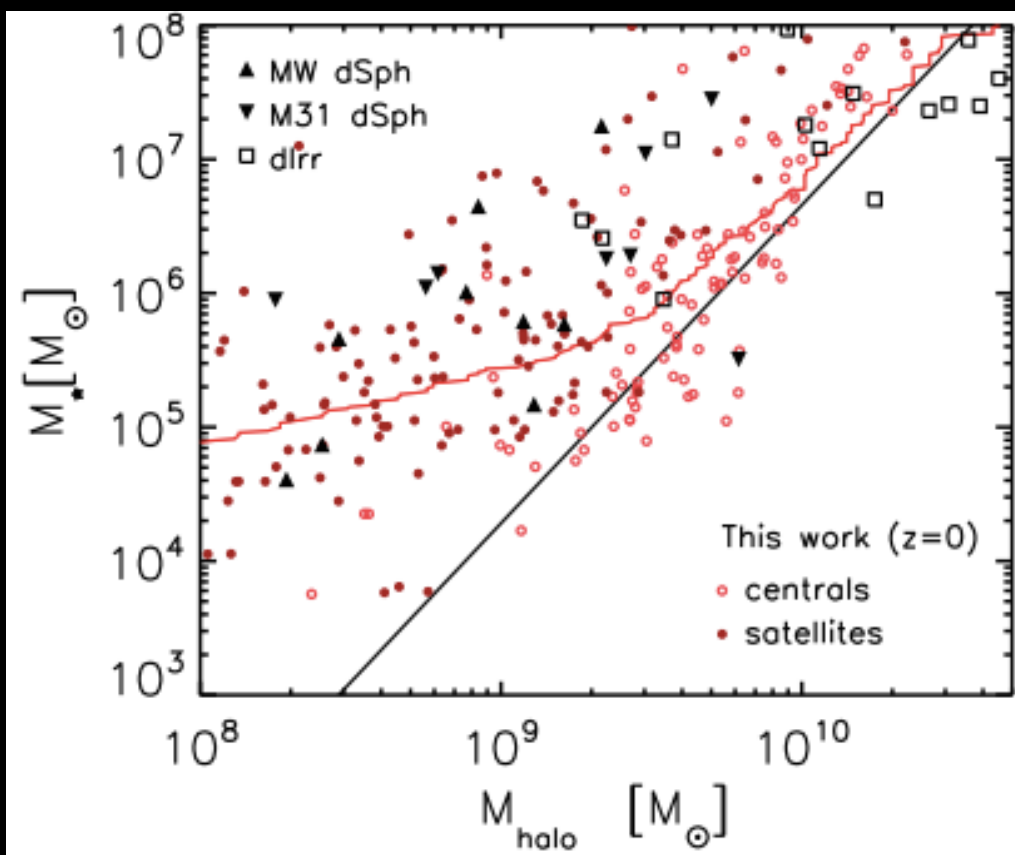
TBTF問題 = 中心部のダークマター密度が観測のそれよりも系統的に高い
⇒ 中心部のダークマター密度を下げてあげれば良い。
⇒ core-cusp問題と同様の方法(SN feedback)で解決可能かもしれない
e.g., Madau+ 2014; Brook+ 2014; Ogiya & Burkert 2015

Madau+ 2014: 孤立系矮小銀河シミュレーション(N-body+hydro)
銀河サイズ、星質量、金属量、星形成史を再現



Revisit TBTF problem

重いサブハローには**必ず明るい**矮小銀河が出来るのだろうか？
= Abundance-Matching は low-mass 側で適用して良いのか？



Sawala+ 2014

- ・高解像度シミュレーション
- ・バリオンを考慮した
低質量側のAMを調べた。



- ・AM method fails at low mass halos
- ・軽いハローにも明るい矮小銀河は
形成可能

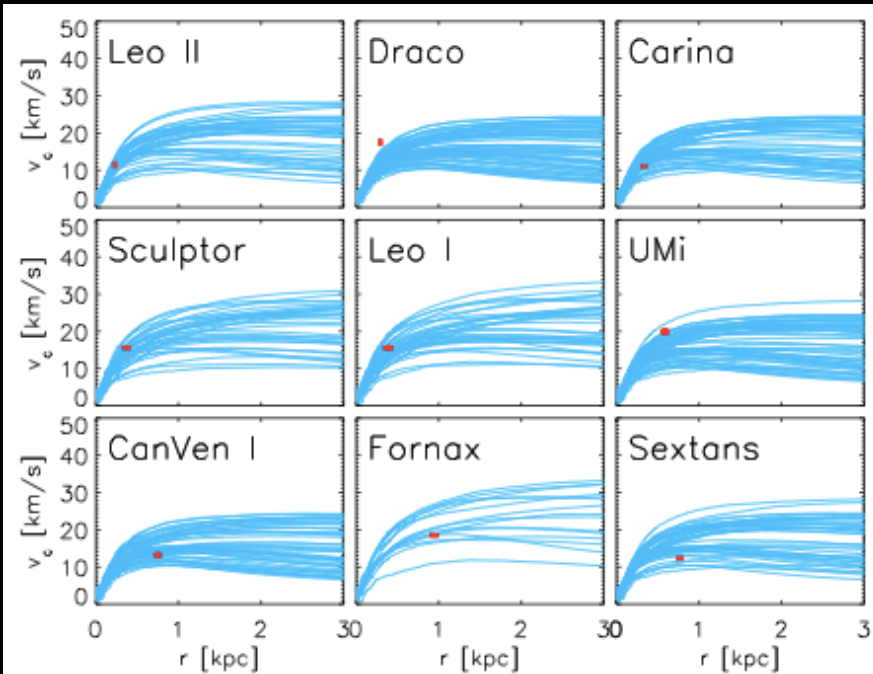
Revisit TBTF problem

The APOSTLE simulations: solutions to the Local Group's cosmic puzzles

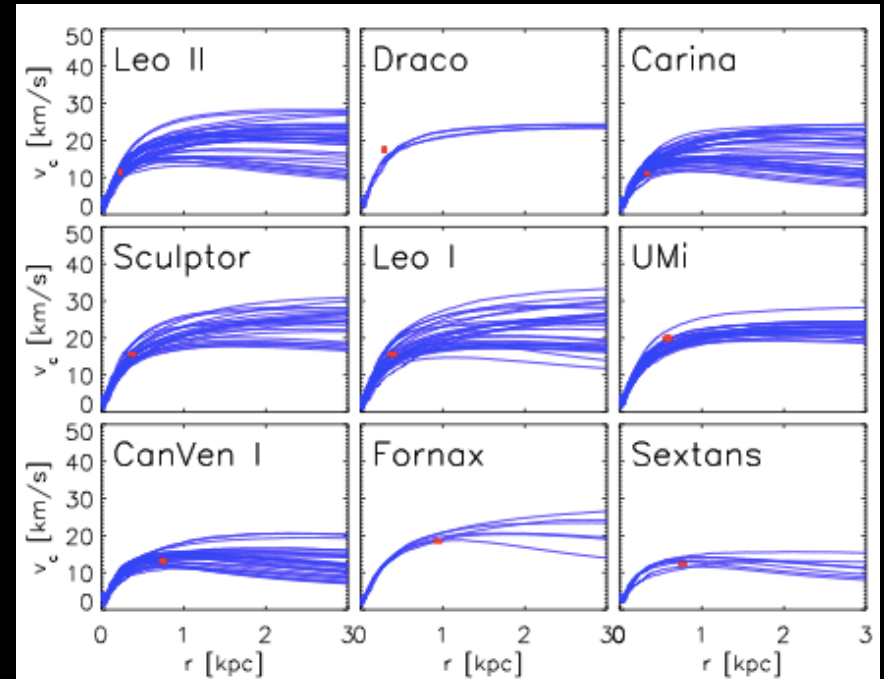
Till Sawala^{1,2*}, Carlos S. Frenk¹, Azadeh Fattahi³, Julio F. Navarro^{3,4}, Richard G. Bower¹, Robert A. Crain⁵, Claudio Dalla Vecchia^{6,7}, Michelle Furlong¹, John. C. Helly¹, Adrian Jenkins¹, Kyle A. Oman², Matthieu Schaller¹, Joop Schaye⁸, Tom Theuns¹, James Trayford¹ and Simon D. M. White⁹

コア構造を作る作らないに依らず、矮小銀河の観測結果を再現することは可能。

星質量が一致するsubhalo



星の質量&速度分散が一致するsubhalo



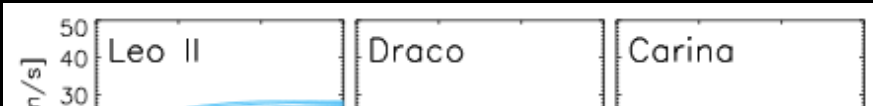
Revisit TBTF problem

The APOSTLE simulations: solutions to the Local Group's cosmic puzzles

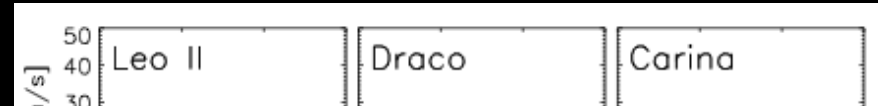
Till Sawala^{1,2*}, Carlos S. Frenk¹, Azadeh Fattahi³, Julio F. Navarro^{3,4}, Richard G. Bower¹, Robert A. Crain⁵, Claudio Dalla Vecchia^{6,7}, Michelle Furlong¹, John. C. Helly¹, Adrian Jenkins¹, Kyle A. Oman², Matthieu Schaller¹, Joop Schaye⁸, Tom Theuns¹, James Trayford¹ and Simon D. M. White⁹

コア構造を作る作らないに依らず、矮小銀河の観測結果を再現することは可能。

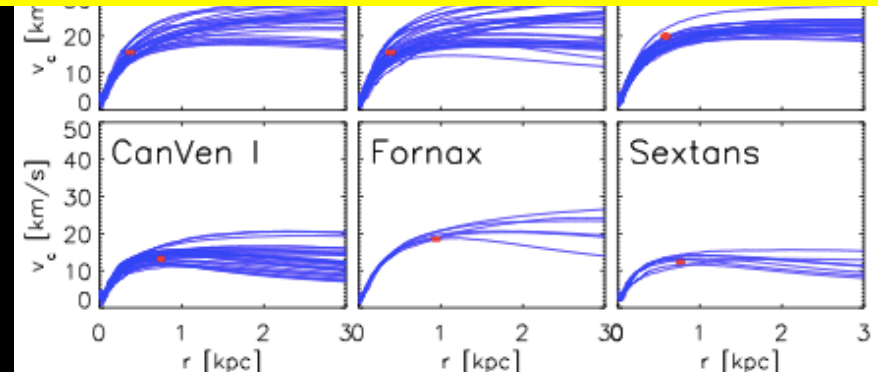
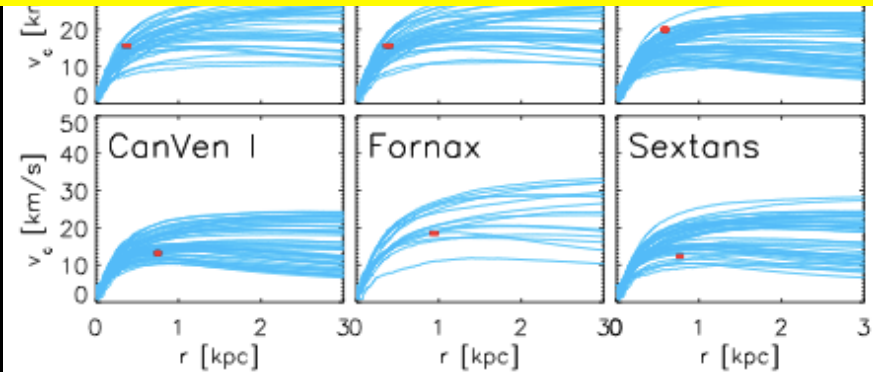
星質量が一致するsubhalo



星の質量&速度分散が一致するsubhalo



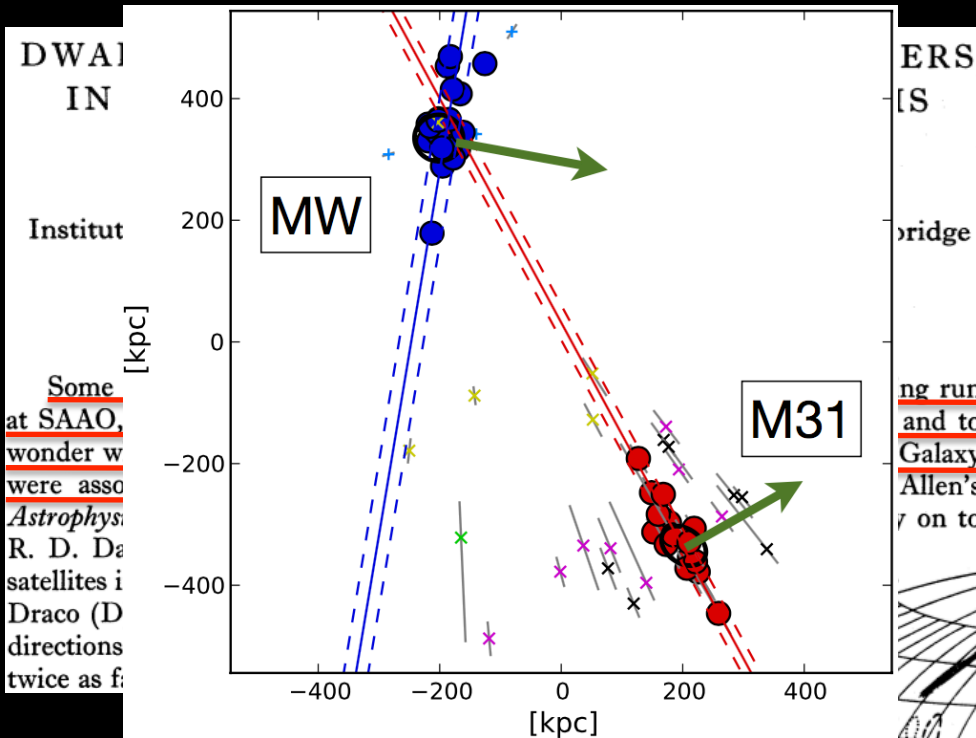
個々の銀河系矮小銀河(とそのダークハロー)がどのような形成・進化をしてきたかを理解する必要がある



~Stable or Unstable~

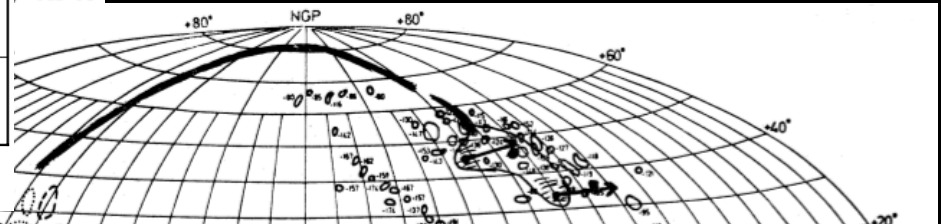
SATELLITE PLANE PROBLEM

Spatial distribution of MW satellites



Lynden-Bellによって1975年には銀河系サテライトの特徴的な分布が発見されていた。

Vast POlar Structure (VPOS)

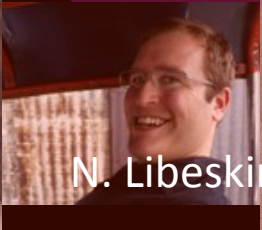


After that...

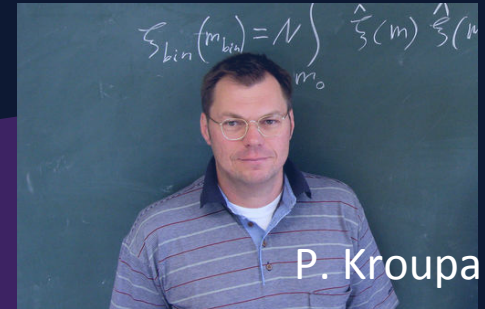
- Flattened distribution of 11 brightest satellites (Kroupa+ 2005)
- UFDs are also associated with disk-like distribution (Metz+2009, Kroupa+2010)
- GCs and half of the stellar and gaseous stream are also included (Pawlowski+2012)
- VPOS also consists of recently discovered UFDs (Kroupa+ 2015)
- Most of these satellites have co-orbiting within the VPOS (Pawlowski & Kroupa 2013)
- Andromeda satellites also distribute large disk-like structure (Ibata+ 2014)

Can Λ CDM reproduce these features?

Λ CDM is correct!



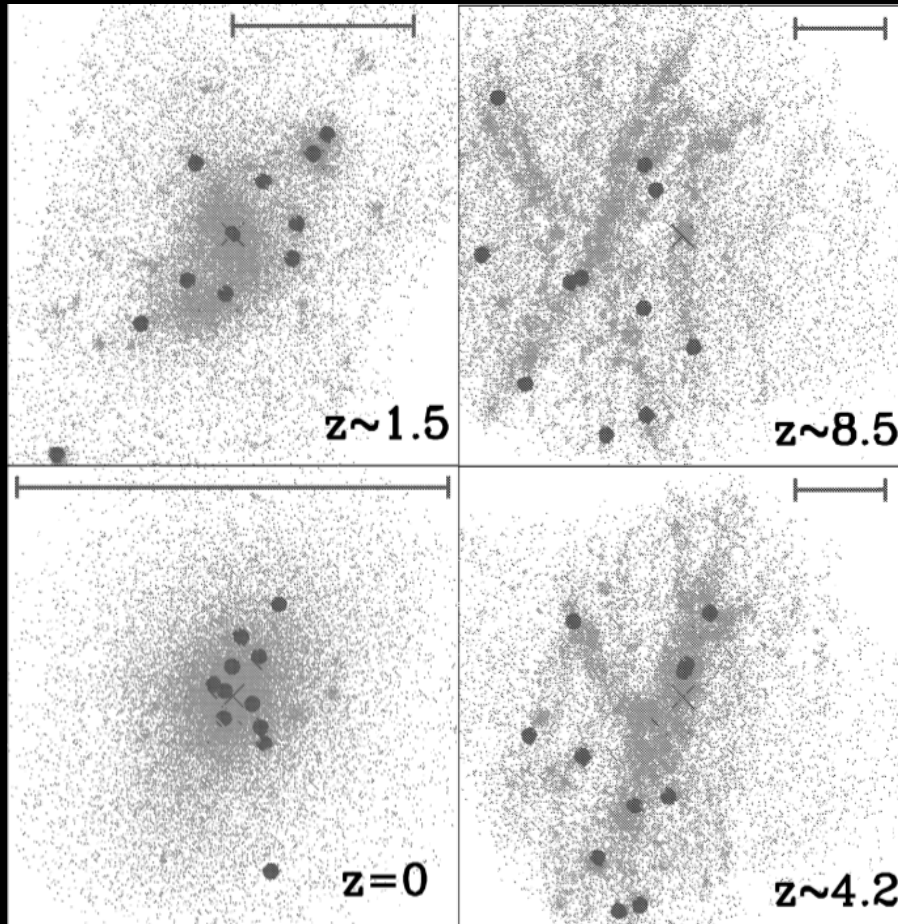
Λ CDM is problematic!



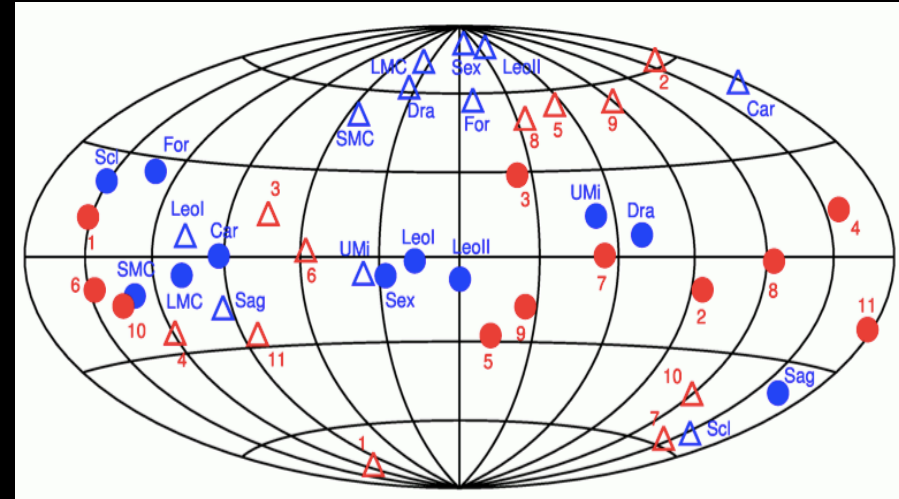
※発表者の勝手なイメージです※

Unsurprisingly Aligned

Libeskind+ (2005): N-body+SAM



Sawala+ (2015): N-body+hydro



赤 : simulated satellites

青 : observed satellites

● : Location in the sky

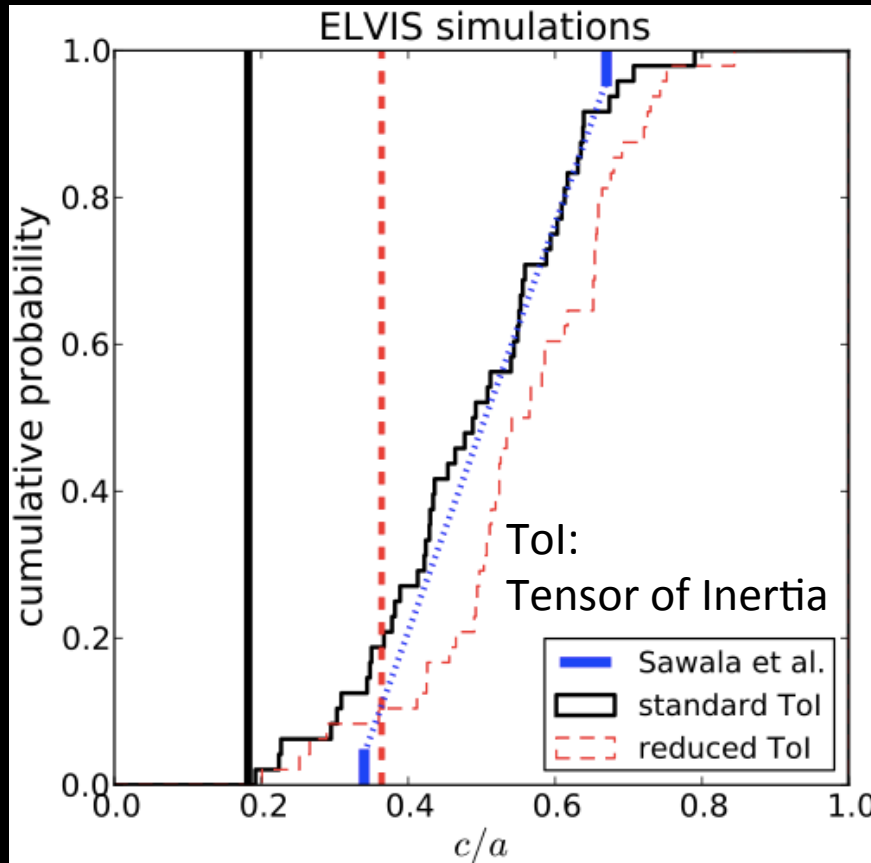
△ : angular momentum vector

サテライトがフィラメントに沿って落ちてきた結果、disk-likeな分布になった。
回転はレアだが出来ないわけではない

On the persistence of this in Λ CDM

Powlowski+ (2015):

Analyzed satellite plane of ELVIS and EAGLE simulation (Sawala+2015)



☆ サテライト分布の扁平度

黒: Standard Tolを用いた解析

赤: Reduced Tolを用いた解析

青: Sawala+15の結果($c/a=0.34-0.67$)

縦線: 銀河系サテライト分布の扁平度

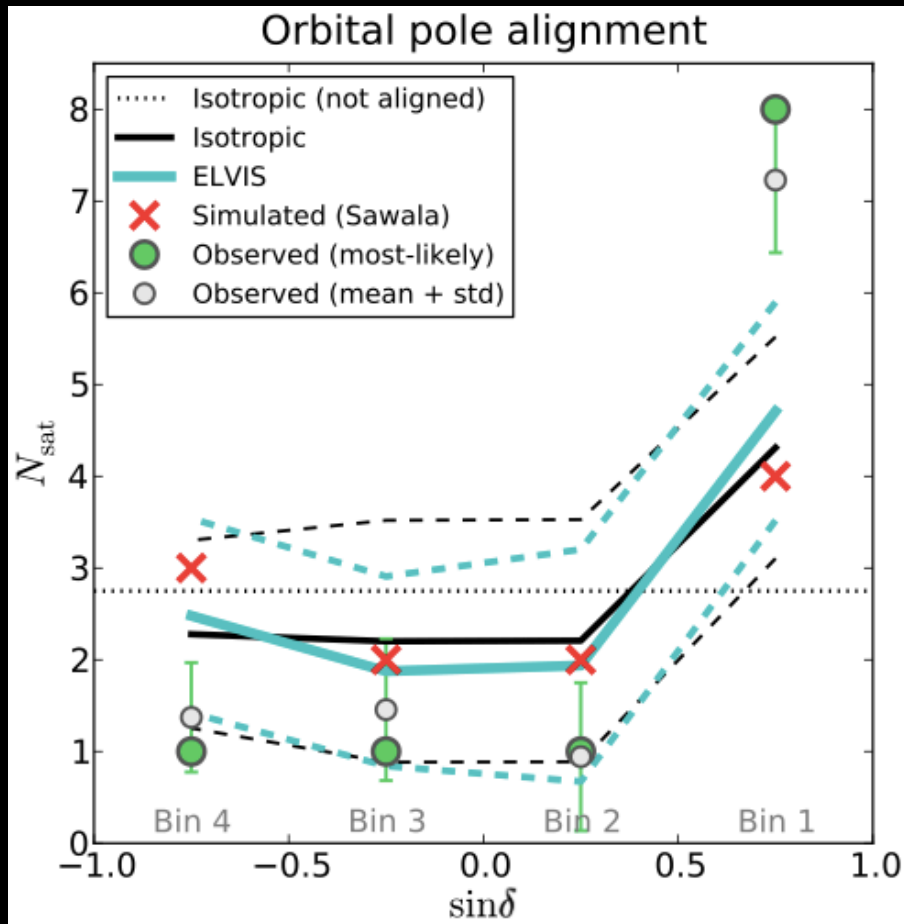
ヒストグラム: ELVIS(バリオン無)の結果

- ✓ Sawala+15の解析手法は扁平度を大きく見積もっている。
- ✓ Salawa+15(バリオン入)とELVIS(バリオン無)の分布は基本的に同じ。
- ✓ **バリオンを入れても観測されるサテライト分布を説明できない。**

On the persistence of this in Λ CDM

Powlowski+ (2015):

Analyzed satellite plane of ELVIS and EAGLE simulation (Sawala+2015)



☆ サテライトの軌道軸分布

- ✓ 銀河系サテライトの軌道軸はディスク分布の垂直方向に集まっている ($0.5 < \sin\delta < 1$ の緑の●)。
- ✓ サテライト分布が等方だと、それを再現できない(黒実線)。
- ✓ ELVIS(バリオン無)、Sawala+15(バリオン入)どちらも等方の場合と変わらない。
- ✓ **バリオンを入れてもcoherentな運動は再現できない。**

Difference of thoughts

Λ CDM is correct!

- ❖ disk 構造に入らないサテライトはどう解釈するのか？
- ❖ 一時的なものであるから、coherent motionは考えてない。
- ❖ unusualでunstableな構造なのでレアケースでも問題ない。

Λ CDM is problematic!

- ❖ coherent motionは安定だからこれも再現されなければならない。
- ❖ この構造はLG以外の銀河にも共通して起きる、usualなものだろう。
- ❖ Λ CDMシミュレーションではdisk構造があまりにもレア過ぎる(0.06%)

MW、M31以外の銀河でDisk distribution & coherent motionが普遍的に起きているのか調べる必要がある。

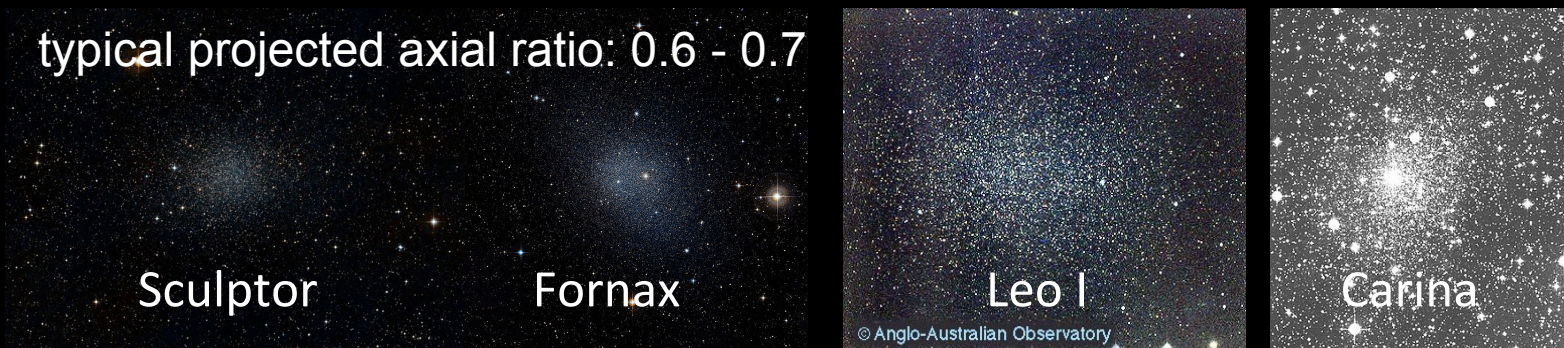
~New issue of Λ CDM theory~

SHAPES OF DARK HALO

Major systematic uncertainty: Spherical symmetry

- ✓ Stellar distributions of dSphs are actually **not spherical**

typical projected axial ratio: 0.6 - 0.7



- ✓ CDM models predict **non-spherical** virialized halos



dSph-sized halo



Major systematic uncertainty: Spherical symmetry

- ✓ Stellar distributions of dSphs are actually **not spherical**

typical projected axial ratio: 0.6 - 0.7



KH & Chiba (2012, 2015b) first constructed **axisymmetric mass models** for dSphs to obtain plausible limits on their density profiles and shapes of their DM halos.



MW-sized halo



dSph-sized halo

20 kpc

New constraint on shape of dark halo in dSphs

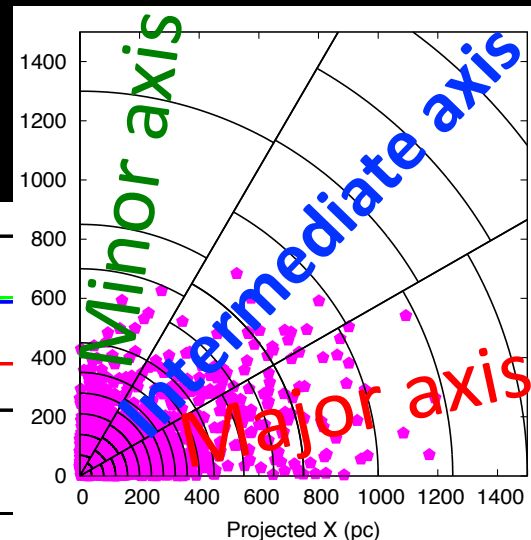
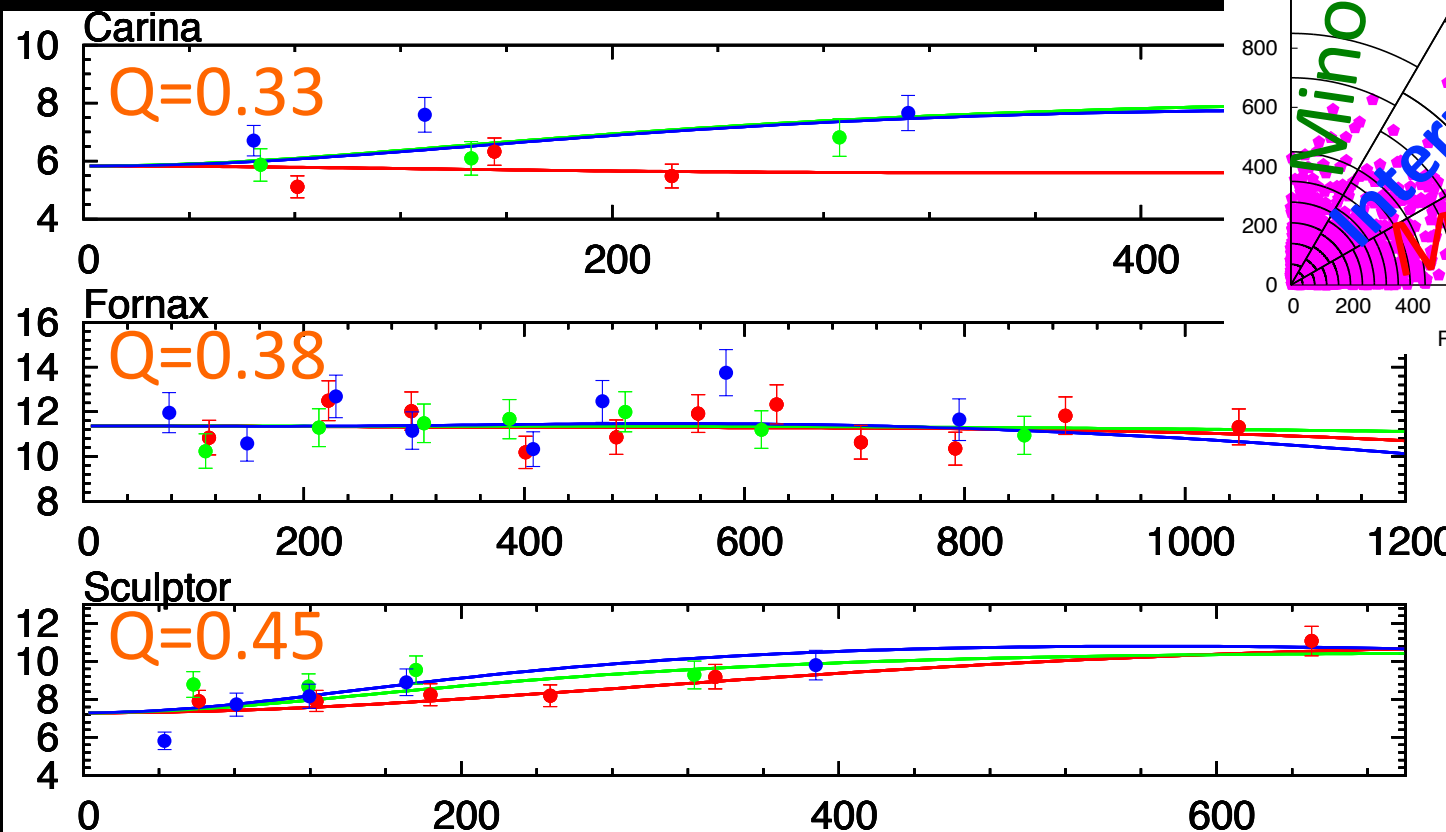
Hayashi & Chiba (2015b)

$$\overline{v_z^2} = \frac{1}{\nu(R, z)} \int_z^\infty \nu \frac{\partial \Phi}{\partial z} dz$$

$$\overline{v_\phi^2} = \frac{1}{1 - \beta_z} \left[\overline{v_z^2} + \frac{R}{\nu} \frac{\partial(\nu \overline{v_z^2})}{\partial R} \right] + R \frac{\partial \Phi}{\partial R}$$

Axial ratio of DM halo: Q

I-O-s velocity dispersion (km/s)



Major axis, Minor axis, intermediate axis (pc)

Comparison with N-body

Vera-Ciro+ 2014:

Recent N-body simulations have predicted that dark subhalos are not strongly triaxial, but rather **statistically oblate, axisymmetric shapes**.

$$\langle b/a \rangle_{\text{subhalo}} \sim 0.93$$

$$\langle c/b \rangle_{\text{subhalo}} \sim 0.84$$

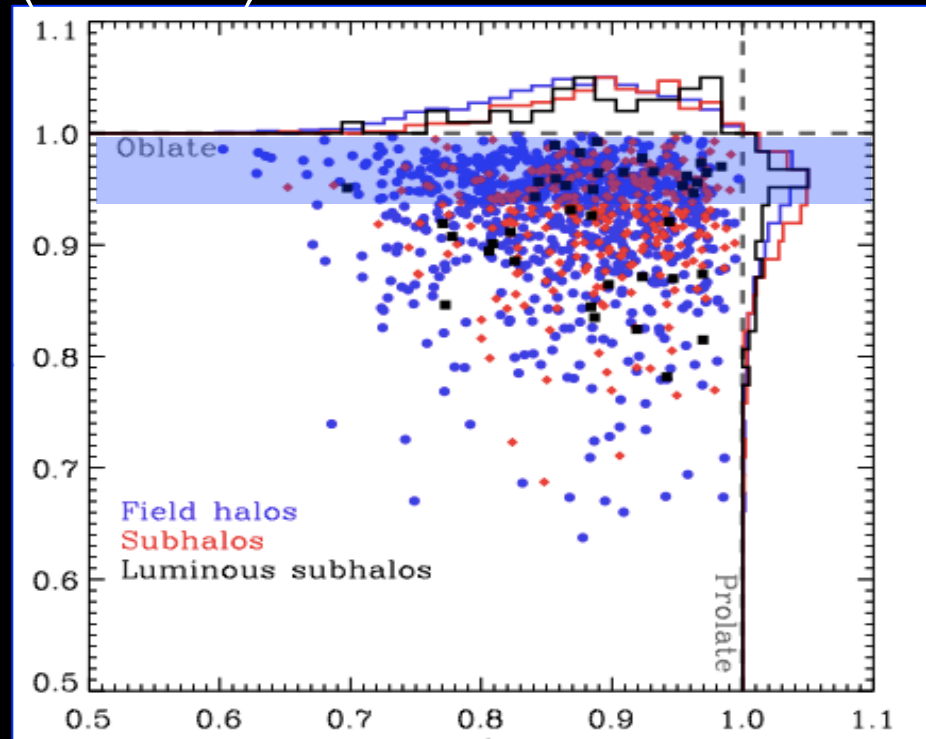


$$\langle Q \rangle_{\text{dSph}} \sim 0.55$$

Much more elongated
than Λ CDM subhalos!!

($a \geq b \geq c$)

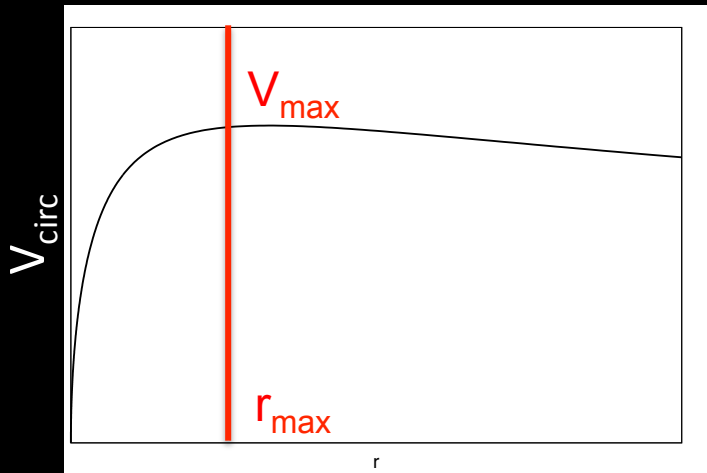
b/a



New universality for the DM halos

KH & Chiba(2015a,b) based on axisymmetric mass models

✓ Maximum circular velocity



We suppose that a test particle perform circular motion in a DM halo potential.

$$V_{\text{circ}}(r) = \sqrt{\frac{GM(< r)}{r}}$$

r_{max} indicates the radius of the maximum value of circular velocity, V_{max} .

✓ DM surface density within r_{max}

$$\Sigma_{V_{\text{max}}} = \frac{M(r_{\text{max}})}{\pi r_{\text{max}}^2}$$

$$\Sigma_{V_{\text{max}}} \propto \rho_s r_s$$

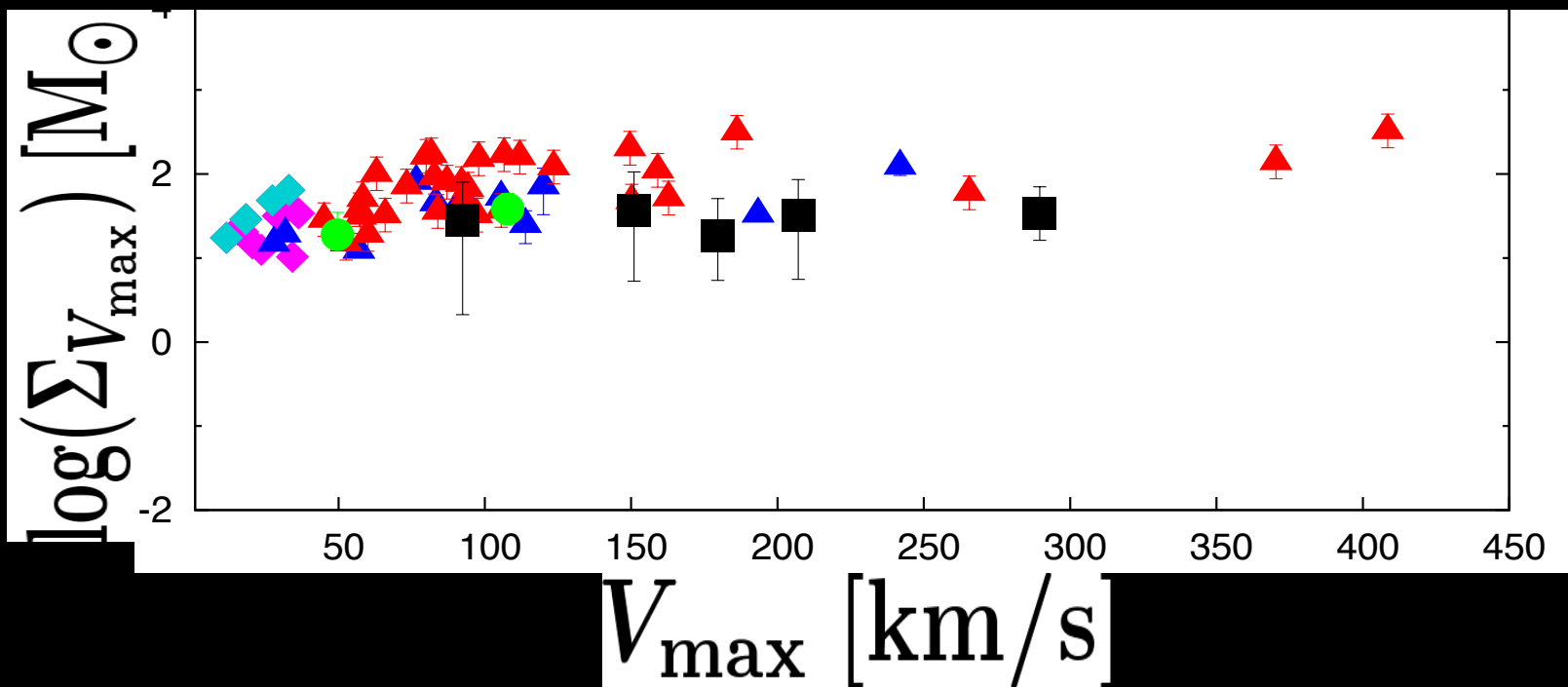
for NEW profiles

$$\rho(r) = \rho_s (r/r_s)^{-1} (1 + r/r_s)^{-2}$$

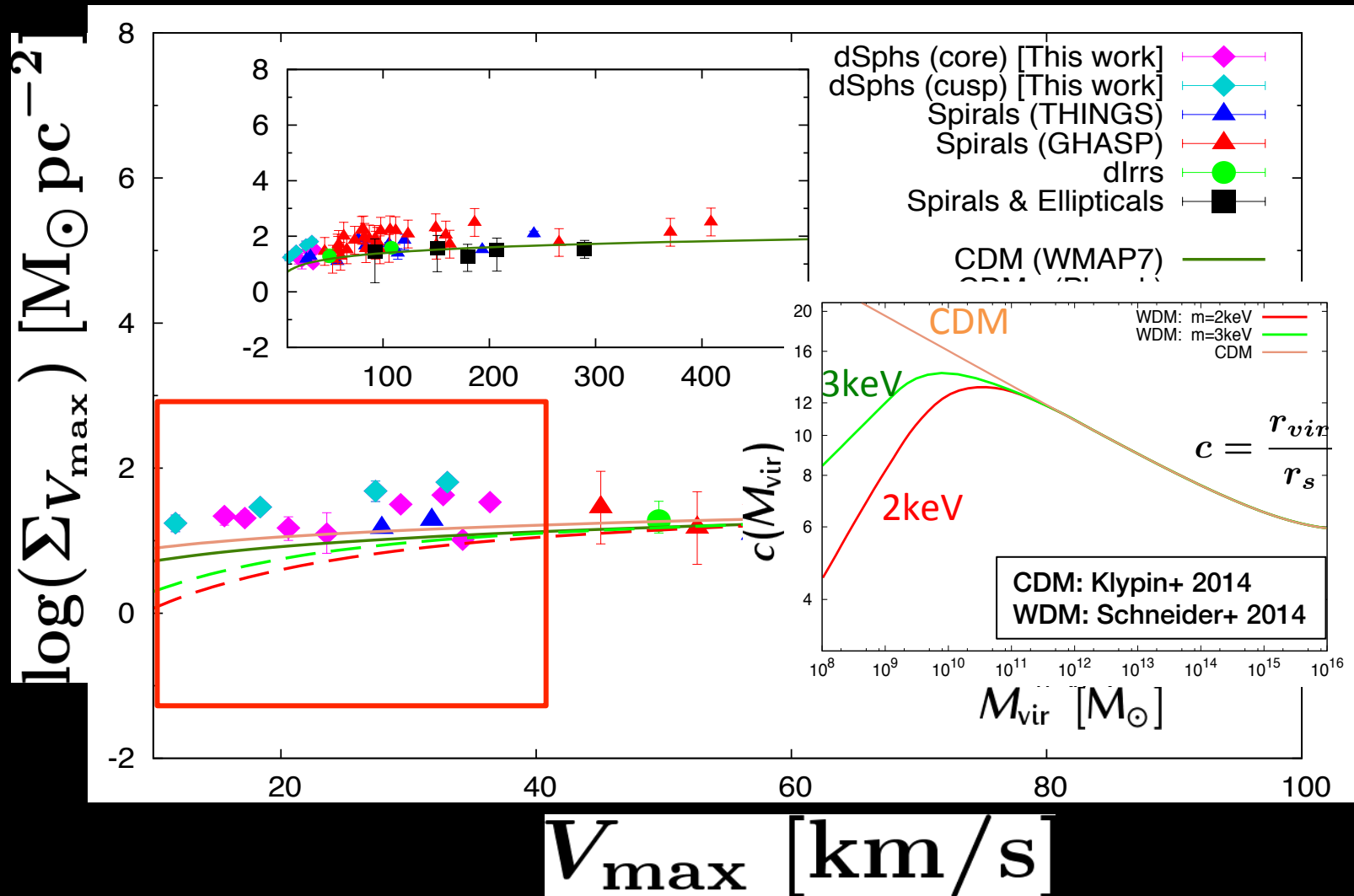
A common surface density scale for dark halos



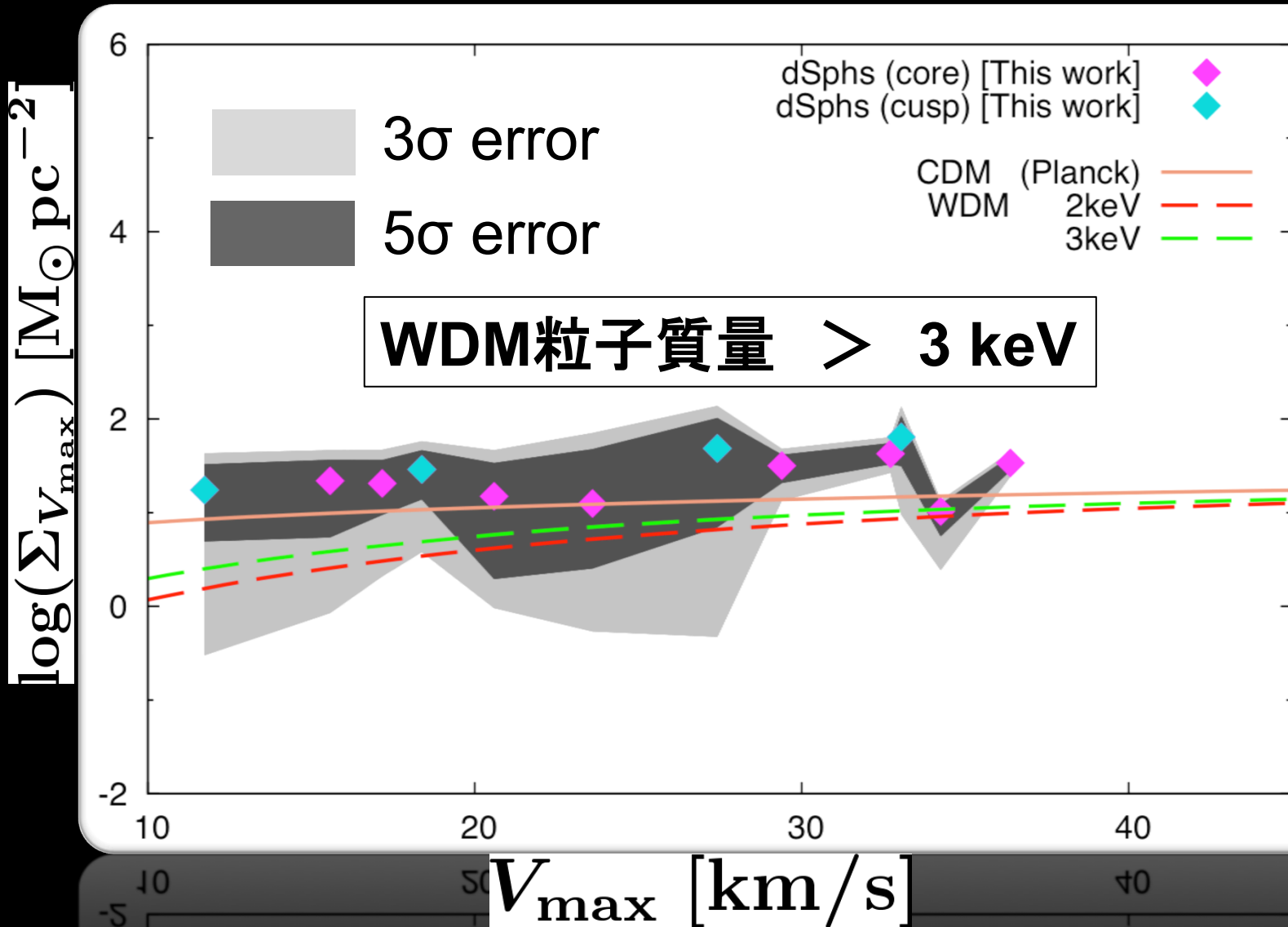
ダークハロー面密度は
銀河の種類・光度・仮定するDM密度分布に依らず
広い範囲で一定の値をとる。



Comparison with dark matter scenario



How cold is dark matter?



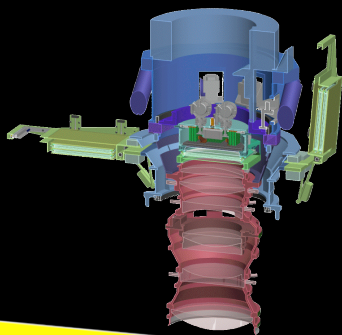
Summary of small scale problems

- **Core-cusp problem**
 - 観測データのアップデートが必要。
 - ダークマターの中心密度分布は星形成に依存する。
- **Missing satellite problem**
 - 次世代大型望遠鏡によって、より遠く and/or より暗い銀河の発見を期待
 - バリオン物理か他のダークマター理論か？結論をハッキリつける方法は？
- **Too-big-to-fail problem**
 - TBTFは本当に問題なのか？
 - ダークハローと星形成の関係のより深い理解が必要。
- **Satellite plane problem**
 - Disk-like構造は stable or unstable? , common or uncommon?
 - Local Group以外の銀河で検証する必要がある。
- **Flattened dark halo problem**
 - 新たな Λ CDM理論の問題点。
 - 潰れたダークハローを作るシミュレーションは今のところ無い。

FUTURE PROSPECTS

第4回観測的宇宙論ワークショップ

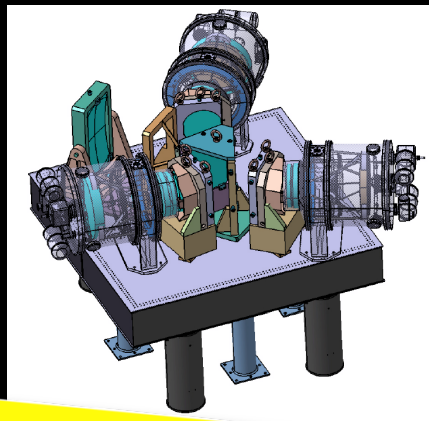
観測的近傍宇宙論のこれから



2014

Subaru/HSC

- Discovery of New UFD
- Hunting a number of faint stars in MW and M31 satellites



2018

Subaru/PFS

- Determining $[\alpha/\text{Fe}]$ and better radial velocities for many faint stars in MW dSphs via PFS with MR ($R \sim 5,000$).



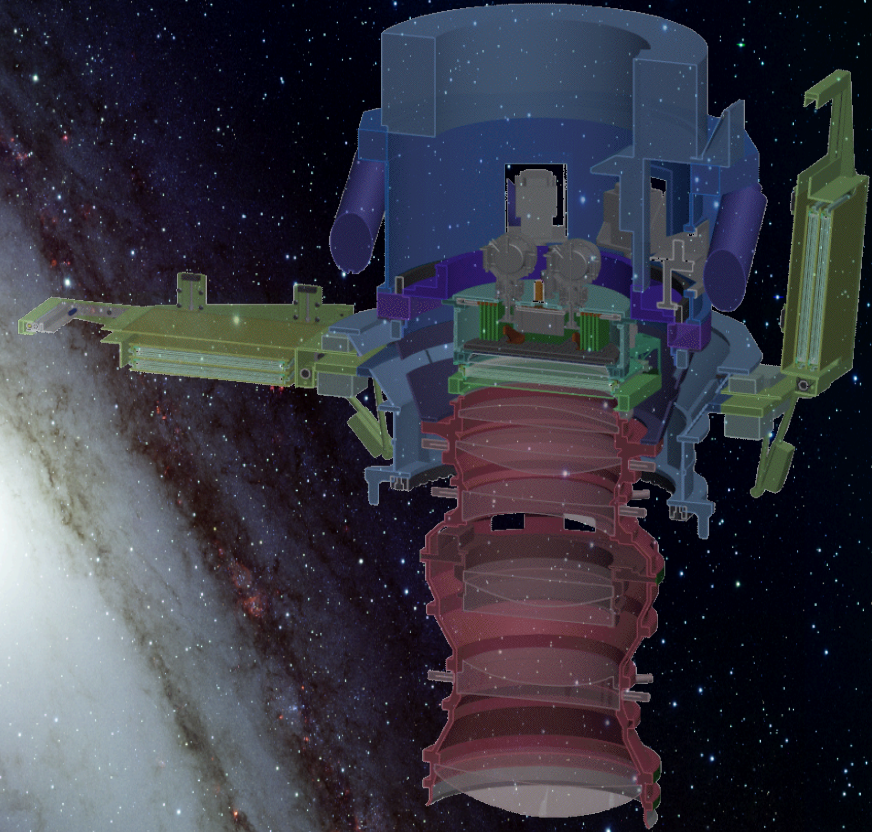
2020

TMT

- Can obtain high-precision radial velocities of member stars via HROS ($R \sim 50,000$).

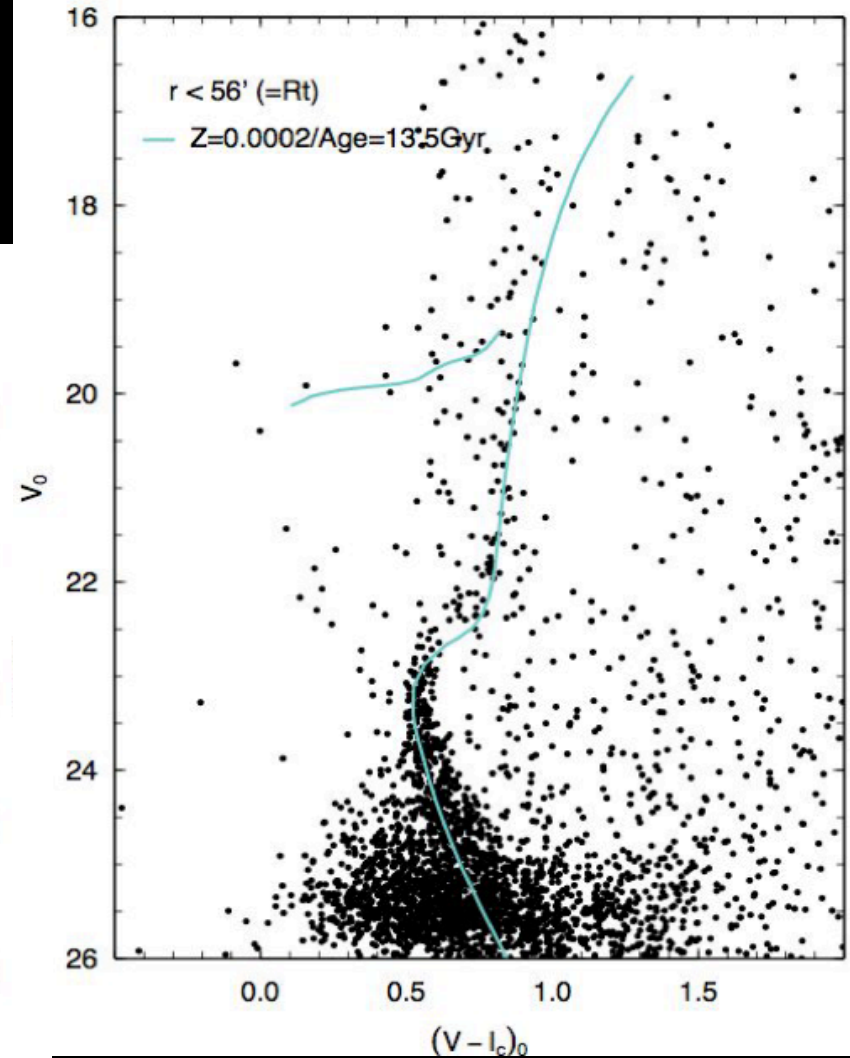
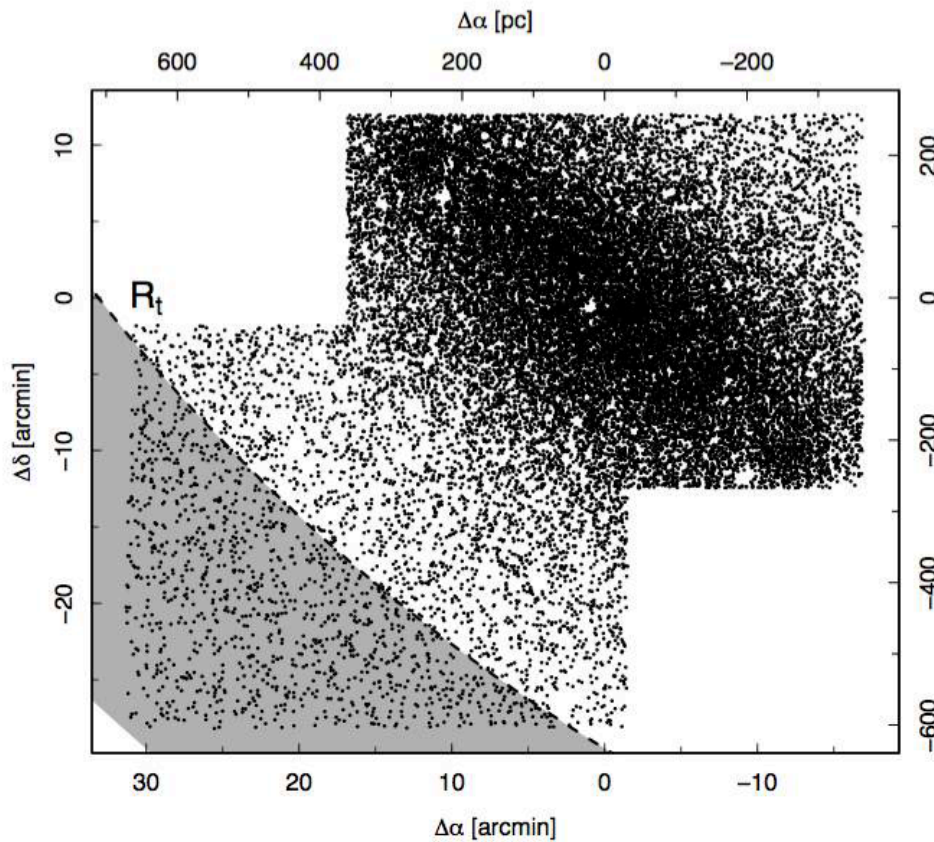


SUBARU HYPER SUPRIME CAM



HSC survey for dwarf spheroidal satellites

S. Okamoto+ S15A



HSC imaging campaign of Galactic dSphs

Japan + Caltech and JHU team

Name	Short exposure (RGBs)			Long exposure (~ MSTO)			Note
	g	i	NB515	g	i	NB515	
Draco (2 fields)	F1, F2	F1, F2	F1, F2	F1, F2	F1, F2	F1, F2	Field number Red: done Black: not yet
Sculptor (4 fields)	F1, F2, F3, F4	F1, F2, F3, F4	F1, F2, F3, F4	F1, F2, F3, F4	F1, F2, F3, F4	F1, F2, F3, F4	
Fornax (4 fields)	F1, F2, F3, F4	F1, F2, F3, F4	F1, F2, F3, F4	F1, F2, F3, F4	F1, F2, F3, F4	F1, F2, F3, F4	
Ursa Minor (4 fields)	F1, F2, F3, F4	F1, F2, F3, F4	F1, F2, F3, F4	F1, F2, F3, F4	F1, F2, F3, F4	F1, F2, F3, F4	
Leo I							
Sextans (19 fields)	F1 – F19	F4, 5, 6, 12, 13, 14, 18	F1 – F19	Not required			

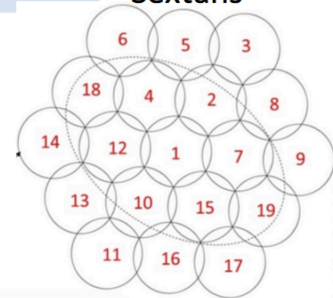
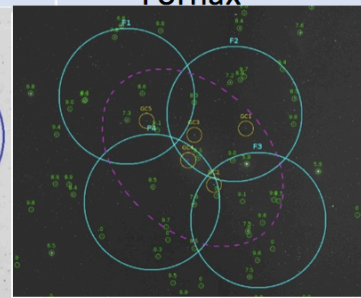
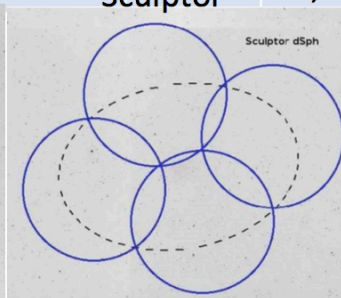
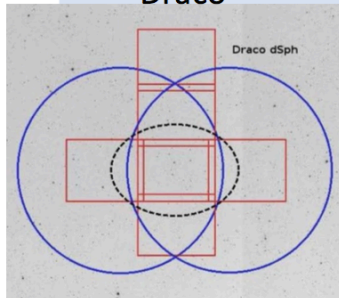
Draco

Sculptor

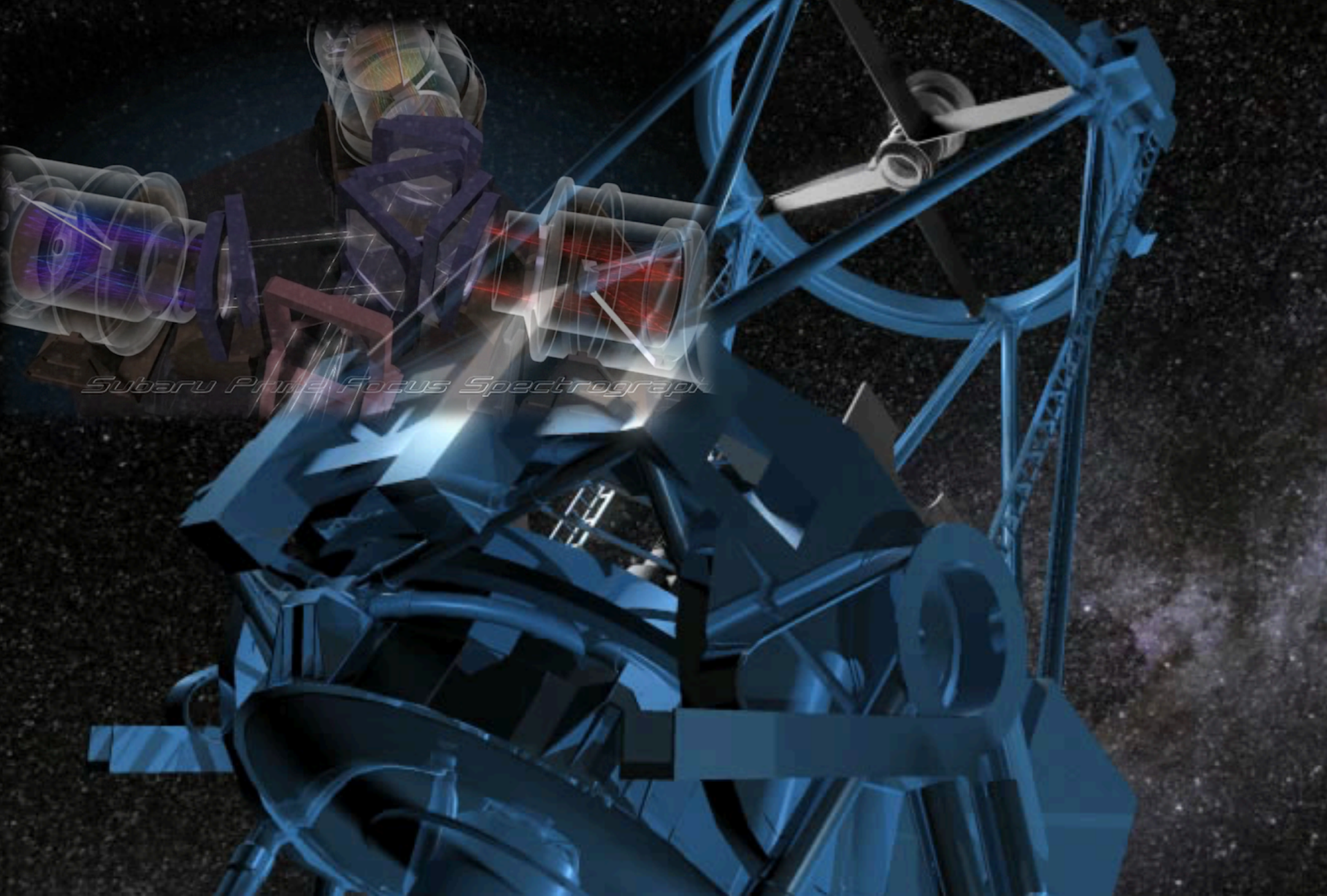
Fornax

Ursa Minor

Sextans



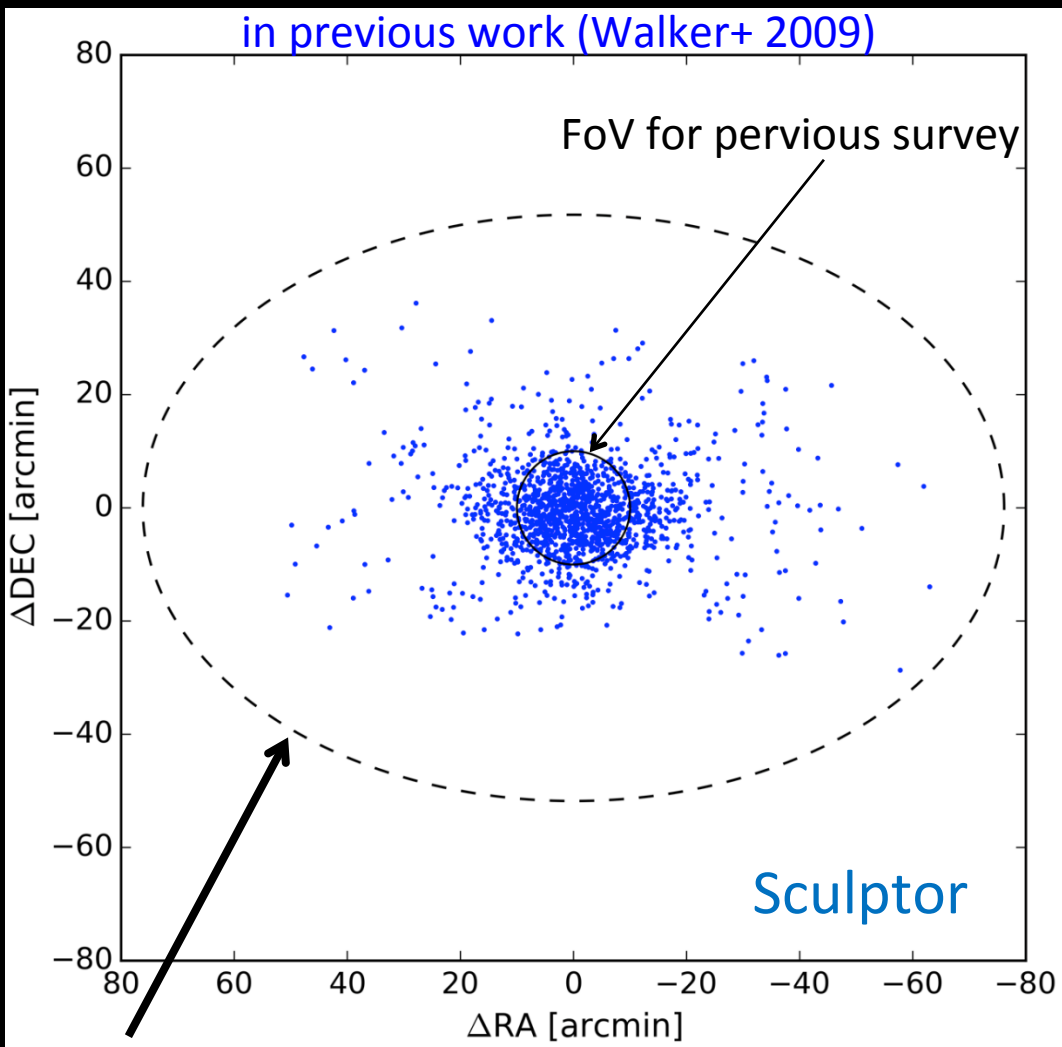
SUBARU PRIME FOCUS SPECTROGRAPH



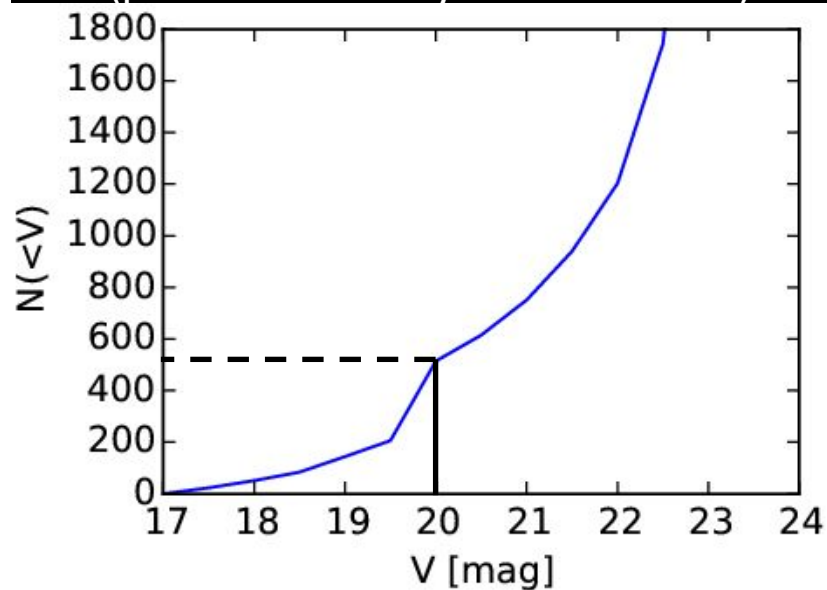
Subaru Prime Focus Spectrograph

Wide & deep survey of MW dwarf galaxies w. Subaru/PFS

Blue dots: spectroscopic targets
in previous work (Walker+ 2009)



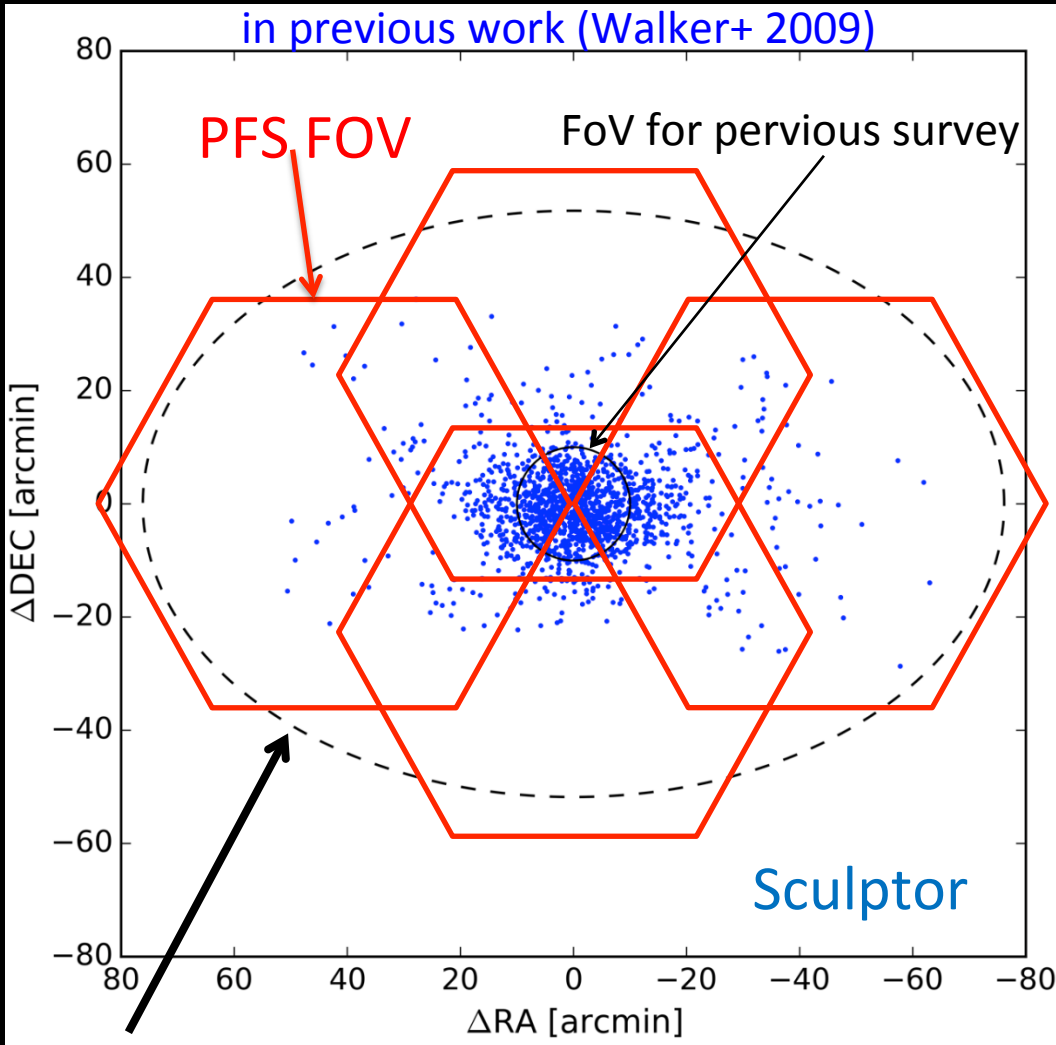
Cumulative number of observable stars
(previous work by Walker+ 2009)



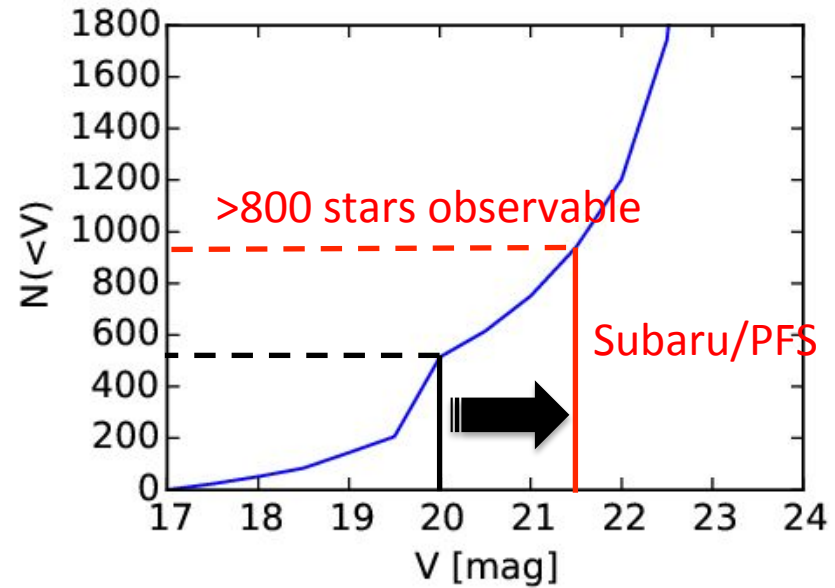
nominal boundary ($r_t \sim 76'$), but more member stars actually exist inside/beyond this limit.

Wide & deep survey of MW dwarf galaxies w. Subaru/PFS

Blue dots: spectroscopic targets
in previous work (Walker+ 2009)



Cumulative number of observable stars
w. Subaru/PFS



Subaru/PFS enables us to measure
a large number of stellar spectra over
unprecedentedly wide outer areas,
where DM largely dominates!
⇒ Best for studying the nature of DM

nominal boundary ($r_t \sim 76'$), but more member
stars actually exist inside/beyond this limit.

PFS Survey

Precise measurement of DM Halo Profiles

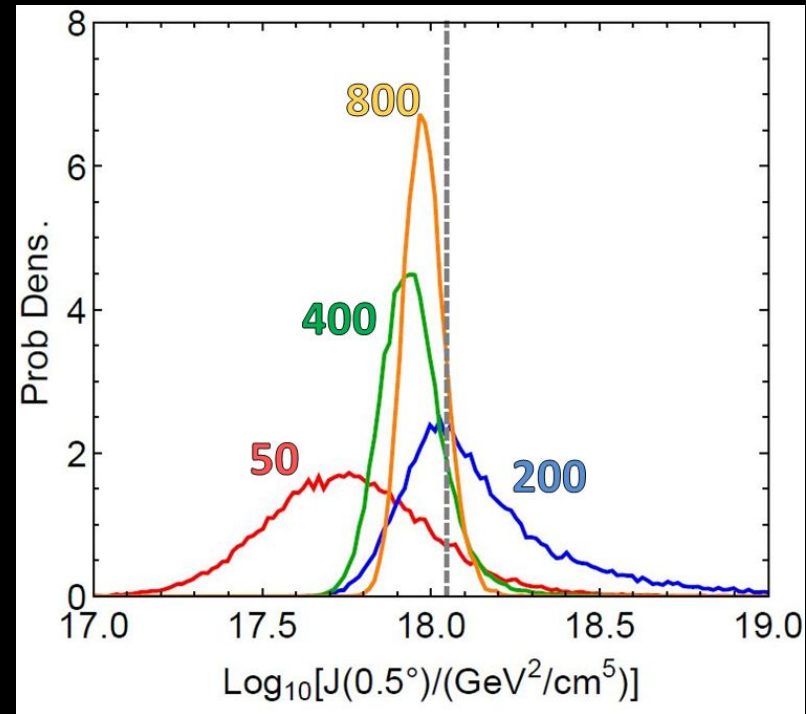
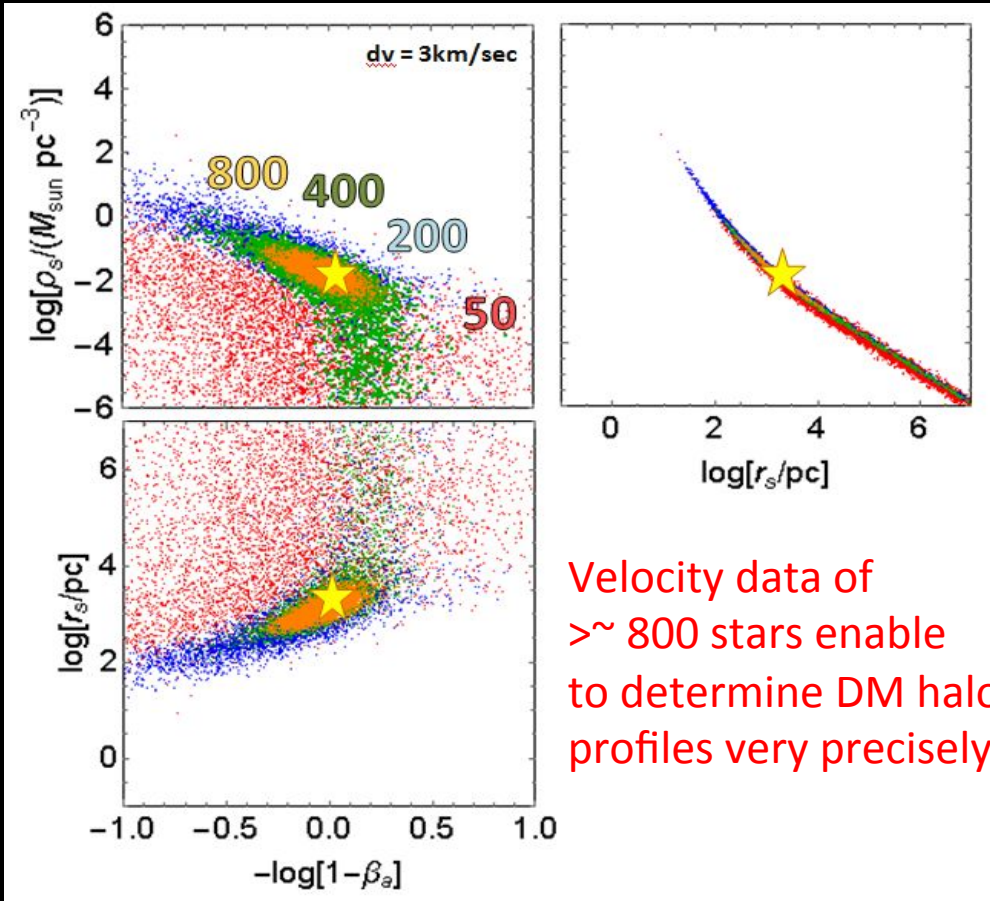


K. Ichikawa

Stellar Velocity Data \longleftrightarrow DM Gravitational Potential
Fit

DM Halo: $\rho(r) = \rho_s (r/r_s)^{-1} (1 + r/r_s)^{-2}$

J-factor = $\left[\int_{\Delta\Omega} d\Omega \int_{l.o.s} dl \rho^2(l, \Omega) \right]$



ークショップ

J-factor is determined very precisely!
 \Rightarrow nature of DM

まとめ

- 非線形領域での Λ CDM理論の検証
⇒ 観測的近傍宇宙論
- 特に矮小銀河スケールでは様々な問題を抱えており、未だ議論中。
- 測光・分光データの大幅なアップデートが必要
⇒ すばるHSC・PFS！
- すばるHSC・PFSによって観測的近傍宇宙論は新たな展開へ。。。